

**HAER No. CA-186-A**

University of California Radiation Laboratory, Bevatron  
(Ernest Orlando Lawrence  
Berkeley National Laboratory, Bldg. 51/51A)  
1 Cyclotron Road  
Berkeley,  
Alameda County  
California

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**PHOTOGRAPHS**

**WRITTEN HISTORICAL AND DESCRIPTIVE DATA**

Historic American Engineering Record  
National Park Service  
Department of the Interior  
San Francisco, California

# Historic American Engineering Record

University of California Radiation Laboratory, Bevatron  
(Ernest Orlando Lawrence Berkeley National Laboratory,  
Bldgs. 51/51A)

HAER No. CA-186-A

*Location:* Ernest Orlando Lawrence Berkeley National Laboratory  
Buildings 51 and 51A  
One Cyclotron Road  
Alameda County  
Berkeley, California 94720

U.S.G.S. Briones Valley, California, 7.5-minute quadrangle  
(1959, photorevised 1968) and Richmond, California, 7.5-  
minute quadrangle (1959, photorevised 1980)  
Universal Transverse Mercator Coordinates: 565.9839E,  
4192.2835N

*Date of Construction:* 1949–1954; Altered, 1957, 1961, 1965–69, 1980

*Engineers/Architects:* Building; Masten and Hurd (architect), Milton T. Pflueger  
(architect), Huber and Knapik (structural engineers), San  
Francisco, California  
Bevatron atomic particle accelerator: William Brobeck  
(engineer)

*Builders:* Pacific Coast Builders, San Francisco, California

*Present Owner:* U.S. Department of Energy (situated on University of  
California land)

*Present Use:* Offices and maintenance shop areas

*Significance:* The Bevatron was among the world's leading particle  
accelerators during a forty-year period from 1954 to 1993  
and is associated with significant contributions in the fields of  
particle and nuclear physics, thus helping to establish  
American leadership in scientific research. In the late 1950s  
and early 1960s, four Nobel Prizes were awarded for particle  
physics research conducted in whole or in part at the  
Bevatron.

*Report Prepared By:* Present and former Berkeley Lab scientists and technical staff: Edward J. Lofgren, William Brobeck, Harvey Syversrud, Richard Gough, Lee Schroeder, Glen Lambertson, Gerson Goldhaber, Bill Wenzel, Lynn Stevenson, Albert Ghiorso, Stan Curtis, and Joe Castro

*Date:* September, 1997

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XBD 9706-00159 TIF  
(August 1996)

Berkeley Lab site map, Bevatron Building (51, 51A).

## Introduction

This report highlights the scientific achievements and significant persons associated with the Bevatron/Bevalac from 1949 (when construction of the facility began) through 1993, when the facility was closed. The report describes the original design of the accelerator machines and buildings, and notes the major design changes that were made as scientific work progressed. A major change took place in 1974 when the Bevatron was connected to a linear accelerator known as the SuperHILAC to create the Bevalac.

The following sections are included in this report: The Bevatron, a subatomic particle accelerator, was the largest, highest-energy accelerator in the world as described in the section entitled *Description of the Bevatron*. *Purpose, Development, and Operation of the Bevatron* describes this accelerator as an essential tool of high-energy physics and discusses the development and operation of the Bevatron and the Bevalac. *Historical Context: Berkeley Lab and the Development of Particle Accelerators* provides an historical background of the Laboratory and the particle accelerators. An account of the initial planning, political processes and funding negotiations, and engaging in a competitive race are presented in the *Bevatron Planning Processes*. *Bevatron Designs* describes in detail the design stages, components, magnet, electric fields, injectors, upgrades, and other accelerator developments such as the Bevalac. *Bevatron Closure* relates the why and when the complex closed. The scientific research and the scientist themselves are recounted in *Overview of the Historic Significance of the Bevatron*. The *Architecture of the Bevatron Building* section describes the context of the construction history. Finally, the *References and Bibliography* section contains a list of sources consulted in the preparation of this report.

## Description of the Bevatron

The Bevatron, a subatomic particle accelerator with an energy potential of 6.2-billion electron volts (BeV), was the largest, highest-energy accelerator in the world when it opened in 1954 at the University of California Radiation Laboratory (UCRL), predecessor of the Ernest Orlando Lawrence Berkeley National Laboratory (Berkeley Lab). The Bevatron had been designed for the study of high-energy nuclear processes of the cosmic-energy (a stream of atomic nuclei of heterogeneous extremely penetrating character that enter the earth's atmosphere from outer space at speeds approaching that of light) range, and was the world's "most productive accelerator of the 1950s" (Seidel, 1983:397). During the 1950s and 1960s, four Nobel Prizes were awarded for particle physics research conducted in whole or in part at the Bevatron.

Like most other UCRL facilities, the Bevatron was owned and funded by the U.S. Atomic Energy Commission (AEC; predecessor of the U.S. Department of Energy) and managed by the University of California. The Bevatron was constructed on land that is under the jurisdiction of the Regents of the University of California and was leased to the AEC (Fig. 1).

## Purpose, Development, and Operation of the Bevatron

### The Bevatron: 1954–1974

The Bevatron was designed by UCRL engineer William Brobeck and staff as a proton synchrotron—a machine that accelerates protons (an elementary particle that is the positively charged constituent of ordinary matter and, together with the neutron, is a building block of all atomic nuclei) until their velocity becomes relativistic as the particles (any very small part of matter such as an electron) approach the speed of light. The Bevatron was a circular accelerator in which particles were kept in a path of constant radius by a magnetic guide-field that increased concomitant with increasing particle mass. A radio-frequency accelerating apparatus imparted energy to particles that were injected into the Bevatron from an external ion source (Cole and Tigner, 1987:152).

Protons in the Bevatron were accelerated by electromagnetic (pertaining to phenomena in which electricity and magnetism are related) forces and all particles moved in the same direction forming a single circulating beam. After the particles were accelerated to the desired energy, the beam was steered toward a target. When a beam of high-energy protons from the Bevatron struck a target, interactions occurred between the speeding protons and the stationary nuclei (the positively charged mass within an atom) of the target. The interactions often produced particles in the target chamber that did not exist before the collision (Fig. 2). Particle accelerators are designed to cause these interactions and permit study of their results (Cole and Tigner, 1987:152).

The accelerator is an essential tool of high-energy physics, used to accelerate particles to very high energy so that the particles can probe the innermost structure of matter and the forces that govern its behavior. In the interaction between a projectile particle and the target particle it strikes, new kinds of particles can be produced that provide clues to the nature of matter. These particles are usually short lived and decay radioactively in a time much less than a microsecond. Such reactions were produced copiously in the first moments of the "big bang" (a theory of the origin and evolution of the universe) from which our universe is believed to have evolved, but are now produced only infrequently in nature by cosmic rays. Systematic study of these particles and their interactions requires controlled, copious production using accelerators. (Cole and Tigner, 1987:153)

The greater the energy of the protons striking the target, the more massive or numerous the newly-created particles were likely to be. The creation of new particles (such as mesons\* or baryons†) is a consequence of the strong force—stronger than the

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\* Any elementary (noncomposite) particle with strong nuclear interactions and baryon number equal to zero.

† Any elementary particle which can be transformed into a nucleon and some number of mesons and lighter particles.



electromagnetic force—which binds protons and neutrons<sup>‡</sup> together in atomic nuclei. Studies of the production and properties of new particles led to the discovery of the strong force. One characteristic of new particles is that they are not stable; they interact or spontaneously break up after very short lifetimes, typically measured in billionths of a second. Their disintegrations, called decay interactions, are a manifestation of the weak force—weaker than the electromagnetic force.

Deeper penetration of a particle requires progressively higher energies in the bombarding particles. The Bevatron was in the vanguard of physics research in the late 1950s because of its capacity to generate the highest energies produced by accelerators of that period. The highest velocity that protons attained in the Bevatron was 184,500 miles per second, or 99.2% of the speed of light (Fig. 3). This is equivalent to an increase in energy of 6.2 BeV (Barklow and Perl, 1987:13).

The Bevatron was the most powerful accelerator in the world from 1954 to 1959, and dominated the field of high-energy physics until the early 1960s. By the late 1960s, during a period of substantial U.S. government support for physics research, and rapid advances in accelerator design, the Bevatron had been superseded by more powerful accelerators at other laboratories. William Wenzel, who began work at UCRL as a postdoctoral student from California Institute of Technology in 1953, has identified the period 1966 through 1971 as one of "decline and transfiguration" at the Bevatron. An AEC congressional report projected the shutdown of the Bevatron in 1974 (Wenzel, 1993:8).

### **The Bevalac: 1974–1993**

The scientific utility of the Bevatron was extended in 1971 by a proposal promulgated by Albert Ghiorso, a laboratory nuclear chemist, to connect the Bevatron to the nearby SuperHILAC (Heavy Ion Linear Accelerator). This resulted in a hybrid facility known as the Bevalac. From 1971 through 1973, the Bevatron was modified under the direction of Edward Lofgren, Division Head of the Accelerator Division, and Hermann Grunder, a specialist in accelerator design and later Bevalac Group Leader. The SuperHILAC linear accelerator was used as a means for injecting heavy ions into the Bevatron, thereby expanding the research potential from a singular particle source (protons), to ions of every naturally-occurring element.

With the operation of the Bevalac beginning in 1974, the focus of research at the Bevatron shifted from the acceleration of protons to the acceleration of heavy ions (ions heavier than helium) and from high-energy particle physics research to three new areas of research: nuclear heavy-ion physics; medical research and therapy in cancer treatment; and cosmic ray experiments which simulated conditions encountered by astronauts in outer space. After the Bevalac was upgraded in 1981, it was the only accelerator in the world capable of accelerating ions of all the naturally-occurring elements of the periodic table (a table of the elements, written in sequence in the order

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<sup>‡</sup> An elementary particle which has approximately the same mass as the proton but lacks electric charges, and is a constituent of all nuclei having mass number greater than of a proton.

of atomic number or atomic weight), from the lightest—hydrogen—to the heaviest—uranium. The Bevalac retained this distinction and maintained an active research program until the facility was closed by the Department of Energy (DOE) in February, 1993.

Throughout the whole period of its operation, from 1954 through 1993, the Bevatron/Bevalac was used not only by scientists at UC Berkeley but by visiting scientists from around the country, as well as foreign scientists from Europe, the Soviet Union, Israel, Japan, and other countries.

## Historical Context: Berkeley Lab and the Development of Particle Accelerators

### UCRL: 1931–1939

The University of California Radiation Laboratory was organized in 1931 on the main campus of UC Berkeley by physics professor Ernest Orlando Lawrence, who invented the cyclotron, a circular particle accelerator, in 1929 (Heilbron et al., 1981:11). The Laboratory was renamed the Lawrence Radiation Laboratory in 1958, in memory of its founder; in 1971 the name of the Laboratory was changed to the Lawrence Berkeley Laboratory, and in 1996 it was renamed the Ernest Orlando Lawrence Berkeley National Laboratory. The cyclotron provided a "long-sought breakthrough into the realm of high-energy physics" by applying Lawrence's principle of repetitive acceleration. In the 1920s, direct-voltage accelerators had been developed which gave particles a single, accelerative push. The direct-voltage accelerator was, however, severely limited in its energy range. In a cyclotron, accelerating particles travel a spiral path within a relatively small space, receiving repetitive applications of comparatively small voltages. This exposure to many accelerative pushes results in the acceleration of particles to high energies.

The first practical cyclotron, built in 1931 by Lawrence and M. S. Livingston, was an 11-inch instrument (with magnet pole faces 11 inches in diameter) and yielded charged particles of sufficient energy to cause nuclear disintegrations. Rapidly succeeding generations of larger and more efficient cyclotrons (27.5-inch, 37-inch, 60-inch) continued to establish frontiers of new energy ranges and deeper penetrations of the atomic nucleus. University officials rewarded Lawrence for his success with the cyclotron program in 1936 by establishing the Radiation Laboratory as an independent division of the UC Berkeley Physics Department.

The vast potential of cyclotron research at UC Berkeley, and elsewhere, had by that time gained international recognition. With Lawrence's help, cyclotrons were built at other universities in the United States, as well as in Europe, the Soviet Union, and Japan. In 1939, at the age of 38, Lawrence received the Nobel Prize in physics for his invention of the cyclotron and for his pioneering research (Lawrence, 1966:136–149). The award was a triumph not only for Lawrence but for the University of California because Lawrence was the first professor at a public university in the United States to receive the Nobel Prize (Childs, 1968:294).

The physicist and cold war historian Herbert York, one of the early students at the Radiation Laboratory, summarizes in the following passage the substance of the cyclotron invention and Lawrence's enduring contribution to the field of accelerator design:

[The cyclotron] was a machine for accelerating protons and other nuclear particles to high velocities by means of an ingenious combination of oscillating electric and static magnetic fields. Its basic purpose was to probe the properties of the atomic nucleus and to investigate its constituents. There were other machines for this purpose—all were

popularly called atom smashers—but Lawrence's cyclotron proved to be the most powerful and effective. More important, his approach appeared to offer the potential for virtually unlimited further development and extension. In fact, more than half a century later, nearly all of the world's huge particle accelerators are based on concepts that, while different in detail and generally much more elaborate, are the direct descendants of Lawrence's original invention. (York, 1987:11)

#### UCRL: 1940–45

Lawrence's Nobel Prize helped generate funding from UC and the Rockefeller Foundation for the expansion of programs and facilities at the Radiation Laboratory during the early 1940s. Having outgrown its original site on the main campus of UC Berkeley, the Laboratory focused its plans for future development on Charter Hill, University property located east of the main campus, which had a commanding view of the University, the City of Berkeley, and San Francisco Bay to the Golden Gate. This hill, rising above the Greek Theater and the football stadium (existing UC facilities on the main campus), has been seen as a "romantic site" (Heilbron et al., 1981:31) or a "picturesque site" (Gebhard, 1987:4) intended as a showcase for the largest cyclotron ever built—the 184-inch cyclotron. Construction of this "'he-man cyclotron,' the 'father of all cyclotrons'" (Heilbron and Seidel, 1989:466) began in 1940, and has served since that time as a "visually dominant structure [that would] assert the pre-eminence of science" (Gebhard, 1987:4).

Historians J.L. Heilbron and Robert W. Seidel, who have written the definitive history of the early years of the Rad Lab, described the entrepreneurial spirit that drove Lawrence and UC President Robert Gordon Sproul in their quest for newer and bigger accelerators.

The success of the cyclotron had inspired competitors, including two clones of the 60-inch; if the Laboratory wished to stay ahead, it must cross the new frontier where, as cosmic ray studies indicated, 'strikingly new and important things' were to be found. Sproul wanted to keep Berkeley ahead. (Heilbron and Seidel, 1989:474).

These ambitions were fed both by timely scientific innovations and by generous patronage—by private foundations during the pre-war period and federal government agencies during and after World War II. The UC Regents also played a vital role as Laboratory sponsors by approving contracts with the AEC for university management of UCRL and by providing university land for Laboratory expansion (Seidel, 1983:375).

During World War II, UCRL accelerators that had originally been built for physics research were mobilized by the Manhattan Engineer District (MED) for the development of a prototype for electromagnetic separation of uranium (a metallic element in the actinide series, highly toxic and radioactive) isotopes (one of two or more atoms having the same atomic number but different mass number) used in nuclear explosives. The weapons program generated rapid development of UCRL facilities and personnel; by 1944 there were more than thirty buildings and laboratories on the main campus and

Charter Hill, and a staff of more than 1200 scientists, technicians, and engineers (Seidel, 1983:377).

#### UCRL: IMMEDIATE POSTWAR PERIOD

The Bevatron was the first UCRL building to be constructed on the Frank Wilson Tract, a 97-acre parcel which adjoined the main university campus on the north, and Charter Hill (the 184-inch cyclotron area) on the south. After the World War II, the Wilson tract had been considered as a possible site for the United Nations headquarters (California Monthly, 1945:22).

The partnership of the physics community and the U.S. government that had been established for the weapons program during World War II continued during the postwar period. The arms race with the Soviet Union during the Cold War provided new justification for sponsorship of physics research and accelerator projects that had potential military applications (Brown et al., 1989:11).

At the end of World War II, when physicists returned to their laboratories, the enhanced status of nuclear physics was immediately evident. The exciting and dangerous development of atomic energy, with its tremendous implications for national security, stimulated strong popular support for spending government funds on building still larger and higher-energy accelerators. (Livingston and Blewett, 1962 [quoted in Brown et al., 1989:11])

Accelerator development in the years just after World War II was, Heilbron argues, the result of a "trade-off, more or less explicit, between physicists and government. According to this account, university physicists received generous support for research that was little, if any, direct concern to the sponsoring agency, in return for supplying trained manpower and technical advice. Most of the Ph.D.'s trained with AEC funds at university accelerator laboratories did go to work for the AEC in one way or another" (Heilbron, 1989:50-51).

The Rad Lab's contribution to the success of the atomic bomb program during the war ensured government support for the continued expansion of Laboratory programs and facilities in the immediate postwar period. "Lawrence knew that science would be both honorably discharged and held in ready reserve for the national defense and welfare" (Heilbron et al., 1981:46-47). "One of the greatest scientific promoters of his time," (Seidel, 1983:377) Lawrence secured funding from the MED and the AEC (successor to MED) for an ambitious development program that focused on four new accelerators: the 4,000-ton 184-inch synchrocyclotron completed in 1946, initially operating at 380 million electron volts (MeV); a synchrotron (operational in 1947) designed for the acceleration of electrons to 300-million volts; a linear accelerator (completed in November, 1947) incorporating Luis Alvarez's ideas for the use of microwave power (an electromagnetic wave which has a wavelength between about 0.3 and 309 centimeters, corresponding to frequencies of 1-100 gigahertz) to accelerate protons to high energies; and the Bevatron, designed in 1946-8 for the acceleration of protons to energies of over 6 BeV.

## Bevatron Planning Process

The initial planning for the Bevatron occurred in the late 1940s during a period of rapid dissemination of accelerator ideas, fostered both by cooperation among and competition between various research laboratories. William Brobeck, head engineer at UCRL, designed a 10-BeV proton synchrotron in the fall of 1946 after taking an engineer's course on accelerator construction at UCRL in the summer of 1946. The 10-BeV energy limit was set because it seemed "the largest machine that could be made in the near future without departing from the techniques used on machines at present in operation" (Brobeck quoted in Heilbron et al., 1981:76). The physicist I.I. Rabi borrowed copies of Brobeck's plans to persuade officials at Brookhaven National Laboratory (BNL) in New York to undertake a similar accelerator program there. Mark Oliphant, a physicist in Birmingham, England, who had visited UCRL during the War, and was familiar with the concept of phase stability (a principle governing the stability of motion of particles in a synchrotron), had by this time already planned a 1.3-BeV proton synchrotron, scheduled to begin operation in late 1949. (Actual operation of the Birmingham machine was delayed until June, 1953). With this array of competition, "Lawrence knew, therefore, that he would have an uphill fight to win AEC support for Brobeck's machine, which he needed to remain ahead in accelerator design" (Quote from Seidel, 1983:393; Childs, 1968:401).

Political processes and funding negotiations played a crucial role in the design of the Bevatron's energy threshold (Seidel, 1983:394; Seidel, 1989:498; Heilbron, 1989:51). Lawrence first sought approval from the AEC in 1947 for \$9.6 million for a 10-BeV proton synchrotron designed by UCRL's head engineer, William Brobeck. When this proposal exceeded AEC budget limitations, Lawrence cut the energy capacity for the Bevatron in half, to 5 BeV. UCRL physicists Edwin McMillan and Wolfgang Panofsky suggested an energy of 6 BeV, the level estimated to be necessary for the production of antiprotons (Seidel, 1989:498).

In late 1947 and early 1948, UCRL and Brookhaven National Laboratory engaged in a competitive race for design and approval of proton synchrotrons in the 2 to 6 BeV range. Brookhaven National Laboratory countered Lawrence's proposal to the AEC with one of their own for a 2.5-BeV proton synchrotron (a device for accelerating protons in circular orbits in a time-varying magnetic field, in which the orbit radius is kept constant) to produce pions (mesons having a mass from approximately 264 to approximately 273 times that of any electron with positive, negative, or zero charge and spin of zero) in pairs. Lawrence then revised his proposal from a 6.2-BeV machine to a 1.8 BeV (for pion production) which could be expanded to 6.5 BeV by doubling the size of the magnet and quadrupling the generator capacity. The General Advisory Committee (GAC) of the AEC ultimately took the diplomatic course by recommending in February, 1948 that "two machines, aimed at substantially different maximum energies, should be built and that the energies and locations [of each] should be determined as a result of consultation between the laboratories" and the AEC (Seidel, 1983:396).

The GAC recommendation left open the vital question of which laboratory would win approval for a higher-energy machine. On March 8, 1948, Lawrence revised his

proposal again, now calling for a larger machine with a radius of 55 feet, with a primary goal of "the achievement of 6-7 BeV protons." Brookhaven National Laboratory adhered to its original proposal for a 2-3 BeV machine (named the Cosmotron) with hopes of eventual construction of a 10-BeV machine. The GAC approved the two proposals—a 3-BeV Cosmotron and a 6-BeV Bevatron—on April 14, 1948 as "major tools for basic research" (Seidel, 1983:397; Childs, 1968:402).

#### AEC DECISION TO BUILD THE BEVATRON

The Bevatron was planned as the largest accelerator in the world in the mid-1950s. Heilbron has posed the question, "Why was the machine built?" The normal response of the physics community—that the Bevatron was built for pure physics research, specifically for the discovery of the antiproton (negative proton)—is only part of the answer. Heilbron analyzes the AEC's reasons for funding the Bevatron and other postwar accelerator projects (Heilbron, 1989:50-51):

1. The AEC built the Bevatron in order to investigate nuclear forces in the hope that they might be exploited in new weapon technology.
2. The AEC did not build the Bevatron so much to knock the nucleus to pieces as to provide an opportunity to keep the experienced engineering staff at Berkeley together for mobilization in a national emergency.
3. The AEC cared little about particle physics, but much about maintaining good cheer at Berkeley, which was the only one of the Manhattan Engineering District's installations untouched by the severe decline in morale and staff suffered by the district immediately after the war.
4. The Bevatron, despite its uniqueness in energy, is best understood as only the biggest of the many redundant accelerators commissioned at universities in the immediate postwar years by the Manhattan Engineer District, the Office of Naval Research, and the AEC.

The AEC's authorization of the Bevatron, the fourth major accelerator at UCRL in the immediate postwar period, underscored the pre-eminence of the Radiation Laboratory's leadership in high-energy physics. Lawrence's success was due not only to technical and scientific ability but to his effective organization of the Laboratory and political finesse in negotiations with the AEC. "Lawrence could not have succeeded in his courtship of the federal patron had his Laboratory not demonstrated its remarkable facility for reconversion to peacetime research that was attractive to the scientific community as well as important to a fundamental understanding of nuclear forces. Another special feature at Berkeley was that accelerator design and construction, unlike reactor development, did not involve security problems or the use of 'special materials' controlled by the AEC. While Argonne, Oak Ridge, and Brookhaven jockeyed for priorities in reactor development, the Radiation Laboratory steamed ahead on its accelerator projects and abandoned its plans for a reactor. The Laboratory's early postwar successes, peaking in the production of the pion, testified to the high morale and determination of its scientists and engineers, to the effectiveness of the postwar organization, and to the leadership of Lawrence and his senior staff. By accelerating science along the path of crash programs for large-scale technological development in

science, the Radiation Laboratory helped set the tone of modern big science" (Seidel, 1983:399-400).

## PROTON SYNCHROTRON DEVELOPMENT

The British scientist John B. Adams views the Bevatron and other synchrotrons of the postwar period as the beneficiaries of an exceptionally smooth evolution of accelerator design and development that had begun with Lawrence's cyclotrons of the early 1930s.

What happened was that one type of machine succeeded another and as each type reached a limiting energy, sometimes for fundamental reasons but more often because extending its energy would have led to prohibitive costs, a new idea was put forward which overcame these limitations and allowed higher energy machines to be built. The remarkable thing was that these new ideas arrived at just the opportune moment so that the research proceeded rather smoothly from one energy range to the next. When the cyclotrons of Lawrence and Livingston were reaching their energy limit due to relativistic effects causing the particles to drop out of phase with their accelerating voltage, McMillan and Veksler invented phase stability. The cyclotron became the synchrocyclotron and the energy limit was extended from about 20 MeV to nearly 1 GeV. [GeV is equivalent to BeV]. When the huge magnets of the synchrocyclotrons looked like becoming an economic limitation, annular magnets were adopted and the accelerating voltage frequency was tracked with the rising magnetic field to keep the particles circulating at constant radius as their energy increased. This new type of machine, called the synchrotron, enabled the energy limit to be pushed up by another order of magnitude to 10 GeV. (Adams, 1981:105)

The advance in accelerator design represented by the Bevatron and other proton synchrotrons can be shown through a brief comparison with earlier, pre-war accelerators. Accelerators used in nuclear research before World War II were all limited in maximum energy, and could not maintain acceleration indefinitely. In the early cyclotrons, for example, the relativistic increase in mass of protons (an elementary particle that is the positively charged constituent of ordinary matter and, together with the neutron, is a building block of all atomic nuclei) and deuterons (a positively charged particle consisting of a proton and a neutron, equivalent to the nucleus of an atom of deuterium) destroys the validity of the resonance principle for energies above about 25 MeV. In the cyclotron, the magnetic field that guided the particles in their circular orbits was constant in time. The iron magnets that produced the fields got bigger and bigger—up to hundreds of tons—as the energy of the machine increased.

In a synchrotron such as the Bevatron, by contrast, the magnetic fields are designed to increase in time as the particle energy is increased by a radio-frequency accelerating voltage.

A synchrotron is an accelerator for charged particles using the principle of magnetic resonance of the cyclotron and exploiting the characteristics that



these orbits are stable in phase for small deviations from the proper resonance energy to permit a variation of the magnetic field or both the magnetic field and the accelerating frequency during the acceleration. (Lofgren, 1962:807)

The synchrotron principle of magnetic particle acceleration derived from three independent sources all occurring within a few years of each other. The first proposal for a proton accelerator was made by Marcus Oliphant of the University of Birmingham, England, in 1943, although the proposal was not published until 1947. The Bevatron also drew upon the idea of phase stability developed by two scientists working independently—a Russian scientist Vladimir Veksler (1944) and Edwin McMillan of UCRL (1945). Both versions of the phase stability concept “presented methods by which particles in resonance-type accelerators could be kept in resonance with the radio frequency fields indefinitely, and could be accelerated to much higher energies” (quote from Veksler, 1966:202-210; McMillan, 1966:211-212; Livingston, 1952:169).

Phase stability is the:

...observation that particles in such a machine [synchrotron] tend to travel in bunches. Suppose the protons, say, get out of step with each other as they move around the ring. Some will then arrive sooner and some later at the places where they are to be accelerated. Since the accelerating fields are changing with time, things can be accelerated so that a particle that arrives too soon will get a smaller boost than one that arrives on time. The effect on a particle that arrives too late will be just the opposite. The net result is that the particles get locked together in bunches. (Bernstein, 1989:50)

The Bevatron, and other proton synchrotrons, were the “culmination of phase-stable accelerators,” and produced the highest energies of the accelerators built in the immediate postwar period (Livingston, 1969:50). Other postwar accelerators were relatively restricted in energy range. Electron synchrotrons had a practical energy limit of the order of 1 BeV due to the rapid onset of radiation losses. Linear accelerators were not yet well enough developed to venture into the BeV range. The synchrocyclotron required a solid core magnet which at this level of energy was exorbitant in weight and cost.

In the proton synchrotron a ring magnet is used to reduce cost, and protons can be used to avoid radiation loss limitation.

The proton synchrotron uses a ring magnet to produce a magnetic field over an annular region, in which a doughnut-shaped vacuum chamber is located. Protons produced at low energy in an external source can be focused and deflected into the vacuum chamber. The magnetic field guides the particles in a circular orbit of constant radius, and is modulated from low to high intensity as the protons gain energy. An electric field to accelerate the protons is provided at one point in the circular path, so that the particles acquire an increment of energy on each revolution; this accelerating field must be oscillatory in nature and synchronized with the

motions of the ions (an isolated electron or positron or an atom or molecule which by loss or gain of one or more electrons has acquired a net electric charge). Since proton velocity increases with energy, the frequency of the applied electric field must be varied during the acceleration to match the increasing angular velocity of the particles. This frequency must be precisely controlled to provide the correct phase of the accelerating field, so as to maintain constant orbit radius and prevent loss of particles by striking the walls. (Livingston, 1966:243-244)

#### COMPARISON OF BEVATRON AND BROOKHAVEN'S COSMOTRON

Both the Bevatron and the Cosmotron were proton synchrotrons of the race track design with four straight sections between magnet quadrants. The Bevatron also had a straight section for a drift-tube accelerating electrode. Low-energy accelerators were used as injection sources of protons. For the Bevatron, a proton linear accelerator (linac) was used. The Bevatron had a double-magnetic return circuit similar in cross section to the standard cyclotron magnet (Livingston, 1952:173). John Blewett has compared the Bevatron with the Cosmotron.

The basic design features of the Bevatron are similar to those found in the Brookhaven Cosmotron. The proton orbit consists of four circular quadrants about 50 feet in radius separated by field-free straight sections 20 ft. long. The component designs in the Bevatron, however, differ from those in the Cosmotron in most cases. The Bevatron magnet, for example, is roughly symmetrical about the proton orbit, with two magnetic return yokes, one inside and one outside the orbit. The design is less susceptible to yoke saturation effects than is the C-shaped magnet of the Cosmotron, but it does not permit the easy access to the vacuum chamber that is possible with the C-shaped magnet. The radio-frequency accelerating unit is a short drift tube whose capacity is continuously tuned by saturation of a ferrite-cored inductor, whereas the accelerating unit in the Cosmotron is a ferrite-loaded cavity. Injection into the Bevatron is at 10 MeV from a linear accelerator instead of the 4 MeV electrostatic injection used in the Cosmotron. (Blewett, 1954:4)

## Bevatron Design

UCRL built a quarter-scale model of the Bevatron in 1949 to work out design problems. Success with the model prompted the start of construction of the full-scale version in September, 1949 (Childs, 1968:409). The quarter-scale model was sent to the California Institute of Technology, and after upgrading was used for several years to accelerate electrons (Fig. 4).

Progress on the Bevatron was interrupted between 1950 and 1952 by the diversion of Rad Lab scientists to a new project, a materials-testing accelerator (MTA) built at an abandoned naval air station at Livermore, California, 45 miles east of Berkeley. The MTA, a proton linear accelerator designed for the production of critical materials, was considered a top priority after the explosion of the first Soviet atomic bomb in 1949 led to a new period of Laboratory mobilization for national defense. Difficulties in the design and operation of the MTA, and the discovery of new sources of uranium in the western United States, led to termination of the MTA project, and the return of Rad Lab personnel to Berkeley and to the Bevatron in 1952 (Seidel, 1989:501). The Bevatron was in operation by early 1954 and reached the target of more than 6 BeV in April, 1954 (Childs, 1968:409;466).

One of the central questions in Bevatron design was the size of the beam aperture. Brobeck's original design called for a large aperture between the magnet poles, 4 feet high by 14 feet wide, but this would have produced protons of only 1.5 BeV. Work on the quarter-scale model in 1949, and with the Brookhaven Cosmotron (inaugurated in 1952) provided experience that made possible a fine tuning of design for the full-scale machine, and brought about a redesign of the aperture. In 1950, UCRL planned the Bevatron with an aperture of 2 feet by 6 feet for an energy of 3.67 BeV, with allowances for future modification for an energy range of up to 6 BeV. In December, 1951, it was decided to plan directly for a 6-BeV machine, with an aperture of 1 foot by 4 feet.

The diversion of UCRL personnel to the MTA project had delayed the completion of the Bevatron by two years, whereas the Cosmotron began operation in 1952. Yet, the Bevatron profited from the delay because of experience gained from the quarter-scale model and the Cosmotron. "When completed in 1954, the 10,000-ton synchrotron could accelerate well-behaved protons through 4,000,000 turns in 1.85 seconds without their deviating from the median orbit by more than a few inches. Their journey to 6.2 BeV lasted 300,000 miles" (Heilbron et al., 1981:79).

### BEVATRON COMPONENTS

The Bevatron had a magnet diameter of approximately 120 feet, and dominated the interior of the Bevatron Building (Figs. 5-7). The massive ring-shaped electromagnet was divided into quadrants (Figs. 8, 9), producing a magnetic guide-field that kept the protons on a path of more or less constant radius during acceleration. Once during each revolution the circulating protons passed through an accelerating electrode where they experienced a small forward push and gained a little energy. To accumulate high energies they had to pass through the electrode millions of times. Acceleration was accomplished by two electric fields, one at the entrance to the accelerating electrode

and the other at its exit. These fields were produced by a radio-frequency (rf) oscillator connected to the electrode. At every instant during acceleration the energy of the protons, the strength of the magnetic guide-field, and the frequency of the rf had to be perfectly matched to keep the protons in orbit at the proper radius. Because of this requirement, the Bevatron could not deliver a continuous stream of high-energy particles, but instead delivered them in bunches or pulses. The acceleration of a typical bunch took about two seconds. When the desired energy was reached, the protons were extracted for experimentation. Then the magnetic field and oscillator frequency returned to their initial values to prepare for the next cycle. The time from the beginning of one cycle to the beginning of the next was about six seconds.

### THE BEVATRON MAGNET

Almost the entire mass of the Bevatron, except for the shielding, was devoted to producing the magnetic guide-field. The heaviest part was the huge magnet, which contains approximately 9700 tons of iron. In addition, approximately 347 tons of copper were used in the 26 miles of heavy cable in which the magnet was wound (Figs. 10-13).

The whole assembly weighed about as much as a medium sized naval cruiser, and its power requirements are prodigious. The two motor-generator and flywheel sets that supply current for the magnet coil must deliver a peak power of 121,000 kW (kilowatts). The average requirement which must be supplied to the motors by the local power company is close to 6000 kW. The magnetic field is made to rise by applying an essentially direct-current voltage of 14,000 volts to the magnet coil at the beginning of the acceleration cycle...In addition to holding the particles in orbit radially, the magnetic field must also apply vertical control. The magnet is designed to produce a magnetic field that bulges slightly toward the outside of the ring. The effect of the bulge is to constrain the protons to a region midway between the top and bottom of the aperture. Thus the particles are focused into a tightly bunched beam, whose radial position is determined by the balance between energy and field strength and whose vertical position is determined by the shape of the magnetic field. Although in principle the Bevatron could have a truly circular shape, in practice there must be access regions along the path where the protons circulate in the machine for inserting such items as the accelerating electrode, targets, vacuum pumps, etc. The magnet does not cover these regions and therefore the particles travel through them in straight lines. There are four straight sections in the Bevatron; these are called tangent tanks and are designated by points of the compass. The protons are injected into the east tangent tank and are accelerated by the electric fields in the north. The west tangent tank contains target handling facilities. (LRL 1969a:4-5)

### ELECTRIC FIELDS

The accelerating electrode in the north tangent tank is a rectangular tube constructed for the passage of the protons. Protons gain energy when they pass through the electrode, if they enter it when the voltage is positive and rising. To increase

their energy to 6.2 BeV, the protons had to circulate 4,400,000 times and travel a total of about 328,000 miles (Fig. 14).

## INJECTORS

The Bevatron had to have an injection system (Fig. 15) for putting the protons into orbit at the start of each pulse. The main function of the injection system was to pre-accelerate the protons to an energy of 19 MeV (Figs. 16, 17). The system consisted of four main parts:

- 1) An ion source where the protons originated. The protons accelerated by the Bevatron started as constituents of hydrogen gas. Electrons were removed from the hydrogen atoms, leaving behind the nucleus, or proton. The protons were then attracted by a system of electrodes and directed into a Cockroft-Walton accelerator.
- 2) Cockroft-Walton type accelerator often called an ion gun (Fig. 18). This was a kind of high-voltage power supply. Protons entering the tube of the Cockroft-Walton were accelerated to an energy equivalent to the voltage of the power supply, delivering protons at about 480 kV.
- 3) The largest part of the pre-acceleration of protons was accomplished by a linear accelerator, or linac, composed of a cylinder about 3 feet in diameter and 42 feet long. Inside along the axis were 75 metal structures called drift tubes. Protons traveled through the tubes in a straight line; after 74 successive accelerations, the protons acquired the 19-MeV energy desired for injection (Figs. 19, 20).
- 4) An inflector, which directed the beam of protons into the main part of the Bevatron. This was essentially a guidance system that steered the protons into the east tangent tank and then directed them into orbit in the Bevatron. Under very good conditions, about 60% of the beam that entered proceeded into orbit.

## TARGETS AND PROTON ACCELERATION IN THE BEVATRON

Once the protons were in orbit in the Bevatron, the accelerating voltage was turned on. The cycle started when a signal from a master timing device instructed the motor/generators to start forcing current through the magnet coils. When the protons had been fully accelerated in the vacuum chamber of the Bevatron, they were directed to some form of target. With an internal target located in the center of the Bevatron aperture, the basic technique was to make the proton energy too low for the existing magnetic field so that the particles spiraled inward. Originally, all the targets were internal to the main ring and the only particles that left the machine were called secondaries, produced when the primary protons collided with one of the targets. Yet, the massive magnet structure and the magnetic field proved to be obstructions to the placing of targets. In a later development, primary protons themselves were extracted from the accelerator with steering magnets and directed to external targets. They were guided away from the machine after acceleration just as they had been guided into it by the injector at the start.

## Bevatron Upgrades

When the Bevatron opened in 1954, it was the most powerful accelerator in the world. By the early 1960s, its maximum energy of 6.2 BeV had been surpassed by several new machines at other facilities, including Brookhaven's 33-BeV Alternating-Gradient Synchrotron, CERN's 28-BeV Proton Synchrotron, and the USSR's 10-BeV machine at Dubna. From 1958 to 1960, Bevatron director Edward Lofgren headed a group of scientists and engineers in planning a major modernization of the facility, with assistance from Walter Hartsough, who was in charge of operations at both the Bevatron and Bevalac for many years. The machine was shut down in July, 1962, for the improvements, and subsequently reopened in February, 1963 (Figs. 21, 22).

The modifications were made in the following five major areas:

- 1) *Proton Injection System.* A completely new proton injection system was installed for increased beam intensity; it consisted of a 480-kV Cockroft-Walton ion gun and a 19-MeV strong-focusing linear accelerator (Figs. 23 and 24). The new injector was capable of supplying at least 20 times more protons to the Bevatron than the old injector; the higher beam intensity was both more efficient (because of greater opportunities for beam-sharing and simultaneous experiments) and opened the possibility of the study of rare events.
- 2) *External Proton Beam Facilities.* An external proton beam facility was added allowing a beam to strike a primary target outside the machine (Fig. 25); previously, a target had to be placed inside the accelerator for an experiment. To study particles striking an internal target, particle detectors and other equipment had to be set up in the cramped and inaccessible hub area of the machine. The extraction of the primary beam from the accelerator allowed targets to be placed within the large experimental area outside the Bevatron. The other advantage of the external proton beam was that particles with extremely short half-lives would survive long enough to emerge from the accelerator and reach the detectors. In a machine with an internal target, these short-lived particles would not survive long enough to hit an external particle detector.

In 1966, there was a further improvement in the extraction of proton beams through development of an External Proton Beam Facility. This facility, completed in 1967, was built as an addition to the original Bevatron Building. It provided 30,000 square feet of new floor space and allowed simultaneous service of several experimental targets with up to eight secondary target beams.

- 3) *Concrete Shielding.* Tons of new concrete shielding were added to the Bevatron to compensate for the increased beam intensity and to control background radiation levels (Fig. 26). The original wooden shield was a partial wall on the south and west sides. As the beam increased, shielding was added to complete the wall on all sides. Some of the original shielding was 1-foot-square redwood timbers from a dismantled bridge. These were fabricated into a ceiling shield, thereby shielding the control room, and used to create shielding-houses for the experimenters (Lambertson, 1993:6-8). In 1962, the concrete shield ring surrounding the accelerator was increased to a uniform thickness of 10 feet—

creating a concrete igloo-style housing. Experimental equipment was placed at the hub, and a new 7-foot-thick ceiling was built over the entire accelerator. The new shielding was supported by steel beams sunk in an underground tunnel directly beneath the magnet. The new shielding was expected to reduce background radiation to 1/100 of the previous level. This enabled scientists to undertake many experiments not previously possible because of interference from background radiation; it also reduced the necessity for special experiment-shielding houses, freeing space for offices or other functions.

- 4) *Movable Targets.* The increased beam intensity raised residual radiation levels inside the Bevatron tank; whereas previously, routine maintenance had been undertaken by workers actually entering the machine's tank, now such access would have to be kept to a minimum. Pole-face windings and other troublesome parts were replaced, and internal targets were moved, by remote control.

In the early years at the Bevatron, scientists and workers had entered the magnet gap in the Bevatron for inserting targets and making measurements. Physicist Glenn Lambertson recalls the improvisation involved thusly,

With less convenience a person could also roll through the gap itself on a special flat scooter—it was a hot trip both thermally and radioactively. My first job in the gap was that of measuring the pulsed magnetic field. We built a cart to carry the pickup coil; this was made of non-conducting and non-magnetic materials... This contraption, trailing cables, was pulled through the quadrant with a rope. With some fussing, it did work and gave us the data to know the energy of that first beam on April 2nd [1954]. (Lambertson, 1993:4)

- 5) *Control System.* The control system was completely overhauled to eliminate undesired beam-induced resonances. The operator's job was made much easier through better displays and an improved beam control system. This enhanced the monitoring of several variables including strength of the magnetic field, the number of protons in the beam, and position of the beam in the tank.

### **Particle Detectors Used with the Bevatron**

The new particle discoveries that took place at the Bevatron in the 1950s and 1960s were made possible not only through advances in accelerator design but through developments in particle detector technology.

The Laboratory had not been a pioneer in particle detection methods or technology before World War II, but developed a strong instrument section after the war (Heilbron et al., 1981:79–80).

Cloud chambers had, since the 1930s, enabled physicists to produce visual images of subatomic particles. Two electronic counting detectors, scintillation and Cerenkov counters, were introduced about 1950, and were used in the first Nobel Prize-winning experiment at the Bevatron—the discovery of the antiproton. Scintillation counters involved the visual reading of flashes made by alpha particles striking fluorescent

screens; Cerenkov counters tracked the Cerenkov radiation emitted by a charged particle traveling through a substance at a velocity faster than the speed of light.

The bubble chamber, invented by physicist Donald Glaser in 1952, and improved by Berkeley Lab physicist Luis Alvarez, was a visual detector that showed particle tracks in liquid hydrogen.

The liquid in a bubble chamber is heated above its boiling point, but is prevented from boiling by high pressure in the chamber. If that pressure is released for a very short time and then reapplied, the liquid still does not boil. However, if a charged particle passes through the chamber while the pressure is released, the resulting ionization leads to the formation of a string of bubbles along the path of a particle. This string of bubbles is then photographed to produce a picture of the paths or tracks of the charged particles in their passage through the chamber. (Barklow and Perl, 1987:27)

Not all bubble chambers used liquid hydrogen. A UCRL team led by Wilson Powell and Robert Birge worked with propane bubble chambers.

Glaser won the Nobel Prize in Physics in 1960 for his invention of the bubble chamber. He was a UCRL scientist at the time of the award, but the invention had been made when he was a graduate student at the University of Michigan.

The first bubble chamber at the Berkeley Lab, built in 1953, was 1.5 inches in diameter; by 1955, a 10-inch chamber was in use at the Laboratory (Fig. 27). A 72-inch bubble chamber, the largest built up to that time, was completed in March, 1959, at a cost of \$2 million with an additional expense of \$1 million for a computer. This was the first giant bubble chamber, and a prototype of the large liquid hydrogen bubble chambers later used in high-energy physics all over the world. The chamber, weighing 240 tons (not including its refrigeration system) was housed in a new 7500-square-foot building (Building 59) adjacent to the Bevatron (Fig. 28). By 1960, bubble chambers had become the "foremost detectors of particles from high-energy accelerators," replacing the cloud chambers, counters, and nuclear emulsions that had been used as standard detectors of ionizing particles during the 1950s (Bradner, 1960:109; Heilbron et al., 1981:79, 86-90; Ritson, 1961:301-364; Galison, 1989:213-251; Riordan, 1987:75; Bradner, 1960:109-160).

W.A. Wenzel, working in Edward Lofgren's group at the Bevatron, introduced spark chamber detectors at the Laboratory. Spark chambers, first used in 1959, consist of an arrangement of parallel, electrically charged metal plates. A charged particle passing between the plates causes the discharge of a series of sparks from one plate to another; when these sparks are photographed, they show the track of a particle passing through the chamber. Muon and electron tracks, for example, can be distinguished from each other using this method because of the observable differences in particle mass (Bernstein, 1989:42).

By the early 1960s, particle detectors at the Laboratory had achieved a status almost as great as accelerators themselves, and groups specializing in different forms of detector technology were organized at the Laboratory. George Trilling and Gerson



Goldhaber specialized in nuclear emulsions. Donald Gow, who had assisted Alvarez in pioneering bubble chamber development and served as project engineer for several Rad Lab chambers, headed the team on bubble chambers (Fig. 29); Hugh Bradner was in charge of data analysis development; H. H. Heckman's group focused on photographic problems; David Judd ran the electronic computers section. "Particle detection in the age of the bubble chamber came to resemble factory production. Other institutions followed the Rad Lab's lead" (Heilbron et al., 1981:97).

The 72-inch bubble chamber was removed in December, 1966, after being in operation for 7 years and nine months. It was rebuilt and enlarged to 82 inches, and reinstalled at the Stanford Linear Accelerator. The 72-inch bubble chamber was subsequently returned to the Lab and is currently on display.

### **The Bevatron Transformed: The Bevalac**

The focus of this section of the report is on the Bevalac, a hybrid facility created in 1974 when the Bevatron was connected to a linear accelerator known as the SuperHILAC. A detailed account of the SuperHILAC and its predecessor, the HILAC, during the years before 1974, is beyond the scope of this report, but a brief review is included here as background for the history of the Bevalac. As will be discussed, the research role of the Bevatron was transformed by modifications permitting the SuperHILAC to inject heavy ions into the Bevatron.

The HILAC, or Heavy Ion Linear Accelerator, was opened at the Laboratory in April, 1957, to study heavy ions—ions heavier than helium. The HILAC, and a similar machine at Yale University, were the first accelerators built specifically for heavy-ion research. The basic elements of the HILAC were a Cockroft-Walton generator and two Alvarez linacs (linear accelerators) separated by a narrow space:

In the first section the ions are accelerated to about 1 MeV/nucleon and, between the sections, electrons are stripped by passage through a thin foil of beryllium oxide; the ions then enter the second section where they are accelerated to full energy. (Blewett, 1967:452)

The HILAC incorporated technology developed for the MTA Mark I; it made possible acceleration of nuclei as heavy as argon (element 18) to energies up to 10 MeV per nucleon. Among the many achievements of a team headed by Glenn Seaborg and Albert Ghiorso were the synthesis of the elements nobelium (102) and seaborgium (106). In 1961, while Glenn Seaborg was serving as chairman of the AEC in Washington, D.C., Albert Ghiorso led a team that synthesized the element 103, named lawrencium in honor of Ernest Lawrence, founder of the Laboratory (Heilbron et al., 1981:100; Hubbard, 1961:432–3; Blewett, 1967:452–3; Grunder and Selph, 1977:354).

The HILAC was modified and upgraded in 1961, 1965, and again in 1969. A major modification, in 1971–2, warranted a new name for the machine, the SuperHILAC. A new ion source enabled the machine to accelerate beams of all ions up through krypton (an inert, monoatomic gaseous element, present in very small amounts in the atmosphere).

## BEVALAC: THE IDEA AND EARLY DEVELOPMENT

Plans for the upgrade of the HILAC to the SuperHILAC had originally included two improvements: capacity to produce beams of extremely heavy ions of low energy for nuclear chemistry research; and use of the SuperHILAC as an injector for a biomedical synchrotron for biomedical research (LBL, 1968e:55). The second part of this plan—the biomedical research program—was ultimately sacrificed.

The idea of combining the Bevatron with the SuperHILAC was originally conceived as an attempt to restore the biomedical program and to explore the potential of heavy-ion beams in cancer therapy. Albert Ghiorso, a nuclear chemist at the SuperHILAC who originated the idea for the Bevalac, explains,

But now [with the SuperHILAC] we had no high energy capability at all. I had been forced to abandon the biomedical people and I felt guilty about it. Ghiorso considered the idea of a further modification to SuperHILAC to raise the output of the machine to high energies for biomedical research, but was told it would be prohibitively expensive with available technology. (Ghiorso, 1993:3)

Ghiorso, in proposing the Bevalac idea, was also influenced by another important factor. The Bevatron, superseded by more powerful accelerators at other research institutions, was already slated to be shut down. This proposal would give it a new research program (Ghiorso, 1993:4; Heilbron et al., 1981:100; LaMacchia, 1993:6-7).

Ghiorso's idea for the connection between the two machines was to use the SuperHILAC as a heavy-ion source and injector for the Bevatron to combine the best features of both machines—the heavy-ion capability of the SuperHILAC and the high-energy capability of the Bevatron.

Ghiorso recalls that his inspiration for the idea of the Bevalac was a map showing the proximity of the Bevatron to the SuperHILAC, situated approximately 500 feet uphill.

I remember returning from the Accelerator Conference at Chicago and talking to [Frank Selph] about his progress. He happened to have a map of the hill showing the various locations of the tunnels where he was thinking of placing his linac. I noticed that the Bevatron was not very far away from the SuperHILAC and I suggested, somewhat facetiously, that maybe we should consider injecting our beam into that machine! Although I made the remark somewhat in jest I said that we should calculate whether that was at all possible. I thought that someone might ask about such a scheme because the Bevatron was on the list to be shut down within a year or so.

Within a few minutes Frank had calculated that the idea was indeed feasible and the Bevalac was born. Ed McMillan [LBL Director] was one of the first persons that I went to with our idea. His reaction was typical of him, "Why didn't I think of that!" (Ghiorso, 1993:3)

Funding for the Bevalac was secured through the efforts of Laboratory chemist Glenn Seaborg, who had just returned to LBL after several years as chairman of the AEC:

We still had to worry about getting the funds for the 2M\$-transfer line to carry the SuperHILAC beam down to the Bevatron. Although he had just stepped down as Chairman [of the AEC] and had returned to Berkeley, Seaborg still had lots of influence. He called one of the regents of U.C., who in turn called Caspar Weinberger, the Director of OMB [Office of Management and Budget] under Nixon, and persuaded him to place the needed transfer line into the budget. The rest is history! Under the very capable hands of Ed Lofgren and Hermann Grunder the Bevalac became a great and successful accelerator. (Ghiorso, 1993:3)

Ghiorso had accurately predicted that the pulse and energy characteristics of the SuperHILAC beam were ideally suited for injection into the Bevatron. The Bevalac achieved its first beam in August, 1974. By 1976, it was capable of accelerating iron ions, the heaviest ions accelerated in a high-energy beam at that time. Even after the Bevalac facility was in operation, however, both the Bevatron and SuperHILAC continued to operate independently at times; each accelerator maintained its own injectors and developed separate experimental programs.

The Bevalac ushered in a new era of research at the Laboratory. The focus of the Bevatron had previously been in particle physics research; only comparatively light particles [e.g. mesons, protons, electrons (an elementary particle that is a fundamental constituent of matter, having a negative charge, and existing independently or as the component outside the nucleus of an atom), alpha particles, deuterons] were available to experimenters at high energies. Heavy nuclei like nitrogen could be accelerated only to relatively low energies, in linear accelerators like the HILAC. The Bevalac was ultimately capable of accelerating all of the naturally occurring heavy nuclei. Heavy ions injected into the Bevatron from the beam transfer line originating at the SuperHILAC, were accelerated to 2.1 BeV per nucleon for applications in nuclear medicine, nuclear physics, and cosmic-ray experiments. The beam research time at the Bevalac was divided so that one third was for biomedical use and two thirds were for nuclear science experiments—including a wide range of fields such as elementary particle production with heavy ions, nuclear fragmentation, cosmic-ray simulation, and atomic physics. (Alonso, 1977:5).

The Bevalac was the only research facility in the world capable of accelerating to high energies the nuclei of all the elements of the Periodic Table—from the lightest element, hydrogen, all the way up to uranium, the heaviest of the naturally occurring elements (Goldhaber, 1984:2; LaMacchia, 1993:8; Grunder and Selph, 1977:380–386).

The Bevalac, (in conjunction with the 88-inch cyclotron also at the Rad Lab) became the country's leading facility for heavy-ion research, drawing scientists from universities and laboratories throughout the United States, and from all over the world, including China, Japan, Germany, and Israel (Heilbron et al., 1981:102; LBL, 1971:1; Kopa, 1987; Kopa, 1988:1).

## BEVALAC DESIGN

The connection between the SuperHILAC and the Bevatron was made through a 550-foot (175 meter) transfer line, that served as a conduit for a heavy-ion beam traveling downhill from the SuperHILAC to the Bevatron. The transfer line lost 140 feet in elevation, before bending and continuing the remaining 300 feet horizontally in the 50-MeV proton injector line. One hundred twenty-five feet of the hillside line was actually underground, contained in a steel liner pipe. The line used 12 bending magnets and 30 quadrupole magnets to guide the beam along the way; transmission of the beam was tuned through computer monitoring and control (LBL, 1973:1,6; Alonso, 1977:3).

The Bevalac system was developed from 1971 through 1973 under the direction of Edward Lofgren, Division Leader of the LBL Accelerator Division, and Hermann Grunder, a specialist in accelerator design and later Bevalac Group Leader. In addition to the beam line, the Bevalac required four modifications of the existing facilities:

- 1) Additional rf cavity in the SuperHILAC to provide for energetic ions for injection
- 2) Control room in the Bevatron exclusively for biomedical research
- 3) Two experimental caves in the Bevatron for biological and medical work
- 4) Animal handling and tissue culture facility in the Bevatron

The SuperHILAC had two injectors that could provide heavy ions for its own experimenters and for Bevalac researchers at the same time. The first injector, named Eve, was designed to produce ions up to argon, mass 40 on the periodic table. The so-called Adam injector could inject ions as heavy as lead. A third injector named Abel, was added in 1981 to provide ions up to uranium (LBL, 1972b:8; LBL, 1974:1; LBL, 1981a:4).

An improvement program at the Bevalac—a new injector for the SuperHILAC, an upgrading of the transfer line, and a new high-vacuum system in the Bevatron—enabled the Bevalac in 1982 to become the first machine in the country capable of accelerating uranium to nearly the speed of light (LBL, 1981a:4; LBL, 1982:5).

A new particle detection system was developed at the Bevalac for heavy-ion research. The Heavy-Ion Spectrometer, or HISS, was installed in 1980 on the east side of the Bevatron's main experiment hall, and was designed for multiparticle experiments, rather than the single particle experiments that had predominated before that time. The project scientist was Peter Lindstrom; Doug Greiner was group leader with overall responsibility for HISS detectors; Hank Crawford was in charge of HISS facilities. HISS was a system, or workbench, where experiments could be arranged quickly and inexpensively, and where many experiments could be performed simultaneously. The system included a large superconducting dipole magnet, two versatile beam lines, a flexible computer system, and a large experimental cave area, but the heart of HISS was a huge magnet 15 feet high, 21 feet wide, 10 feet deep and more than 1 million pounds in weight. A Laboratory report extolled the virtues of the HISS system.

This powerful magnetic field will do for subnuclear particle beams what a prism does for light—divide and separate out different components, thereby providing a spectrum for viewing and analysis...but HISS will not

include the instrumentation found in a classic spectrometer. Researchers using HISS will provide their own particle detectors and some specialized instrumentation during experiments. (LBL, 1979:26)

## BEVALAC BIOMEDICAL FACILITY

In 1974 the Bevalac was established as a national accelerator facility for biomedical heavy-ion research funded by the U.S. Energy Research and Development Administration (ERDA). Under the terms of the funding, the beam was to be available to all potential users throughout the country. The Bevalac Biomedical Facility, which opened in the Bevatron in 1975, united the biological and physical sciences in a program to use heavy ions clinically for diagnostic and therapeutic radiology. It was specifically designed for tumor, tissue, cellular, molecular, neural, developmental and space radiobiology, radiography, and radiological physics. It included a separate control room, three irradiation caves, and two preparation rooms. Biomedical programs included basic research on cancer, radiological and chemical studies, and research on the nervous system, in addition to cancer therapy and medical diagnosis (Alpen and Lothrop, 1977:13-14).

Cornelius A. Tobias, a pioneer in early cancer therapy research at the Laboratory, noted in 1980 that the Bevalac was the "only accelerator in the world capable of producing heavy ions with substantial beam penetration qualities that are suitable for medical applications in humans" (Tobias, 1980:8).

The best ions for biological and medical work range from neon (element 10) through iron (element 26). After being generated in the SuperHILAC, these heavy ions were steered by magnets through a vacuum line into the Bevatron where they were further accelerated to higher energies and then directed to one of three experimental rooms—the Radiological Cave, the Biological Cave, or the Minibeam Room. The Minibeam Room was located on top of the shielding roof directly above Channel II. The beam was brought up through a hole in the roof blocks at an angle of 27 degrees and ran parallel to an inclined optical rail system inside the Minibeam house. This facility was designed for low-energy, low-intensity operation with extremely fine beams for microscopic radiobiological work and microsurgery (Alonso, 1977:5).

Accelerated heavy ions are particularly well suited to biological and medical research and therapy. They penetrate deeply and deposit their energy abruptly as they stop in a target, which makes them especially appropriate for diagnosis and treatment of many diseases, including some types of cancer. Most of the destructive force of the beam is concentrated at its stopping point in the tumor without damaging the surrounding healthy tissue. This is in contrast to conventional radiation therapy; x-rays, for example, deliver a dose that steadily decreases with depth, so that surface tissue is more likely to be damaged than the deep-seated tumor (LBL, 1980c:4).

Joseph Castro, M.D., who directed the biomedical program at the Bevalac, has explained that,

There are two real advantages for this kind of radiation, the first of which is that since it's a charged particle, it can be much more precisely delivered than the standard kinds of high energy x-ray treatment that you would

commonly find in a hospital. And that precise delivery means a greater effect on the tumor and less side effects in terms of normal tissues around the tumor. The other big advantage is the biology of these particles, that is the biological effects are greater, and therefore, there's a better chance of killing tumor cells with the Bevatron radiation than with the standard kinds of radiation. (Quoted in LaMacchia, 1993:8-9)

The patient therapy program at the Bevalac began on a small scale in the spring of 1979. By 1980 patients were treated four days a week. Physicist Jose Alonso headed the biomedical team at the Bevalac in 1980, with patient monitoring by Berkeley Lab radiotherapists and local hospitals (LBL, 1980c:4).

Dr. Castro described the treatment of patients in the Bevalac Biomedical Facility in detail:

So the patient would typically be seated in [a] chair and in a mask, and the radiation beam came from the Bevatron, where it was accelerated into this room in a horizontal fashion, and would pass through a number of devices to shape the beam to determine how deeply it would penetrate, and then through these measuring devices to be sure that we had the right dose and energy, and finally intersect the patient, coming to rest in the tumor. (Quoted in LaMacchia, 1993:9-10)

#### BEVALAC RESEARCH IN NUCLEAR CHEMISTRY AND PHYSICS

The Bevalac was the only laboratory in the country capable of simulating the high-energy heavy-ion component of primary cosmic rays; this component of primary cosmic rays consists mostly of hydrogen nuclei (protons) but also some heavier elements that are always streaming toward earth from outer space. Relatively little was known of primary cosmic rays, because naturally-occurring cosmic rays interact with gas molecules in the upper atmosphere and form secondary particles before reaching the earth. The Bevalac played an important part in the NASA space program, studying how cosmic radiation reacts with matter. Instruments were exposed to beams to evaluate sensitivity to cosmic radiation. Biophysicists Stan Curtis and Aloke Chatterjee developed models for assessment of the health risks to astronauts due to heavy-ion exposure during long-term space missions.

Biophysicist Cornelius Tobias conducted controlled experiments to test the veracity of astronauts' reports of seeing flashes of light in outer space. He exposed himself to a beam at the Bevalac and observed a visual phenomenon never before seen on earth. "You see visual flashes," he recalled. "It is an exhilarating sensation. It is as though you are looking into the universe itself."

In the late 1970s, experiments at the Bevalac produced the world's first data on central collisions of energetic beams of heavy ions and heavy-element targets. In these experiments, a beam of heavy ions such as neon 20 was accelerated to near the speed of light and steered to collide with a very heavy target nucleus such as uranium. The Art Poskanzer/Hans Gutbrod Group, which included both nuclear chemists and nuclear physicists, measured such reactions in their scattering chamber at the Bevalac, and worked on a description of the reaction known as the fireball model. According to this

model, nucleons in the area of impact momentarily fuse together, forming a kind of nuclear fireball, which then decays in an explosion of particles. The fireball reached a temperature of 50 MeV, which was believed to be the hottest nuclear matter ever seen at that time. Art Poskanzer noted that "it took both the physicist's and the chemist's point of view to come up with the fireball model" (LBL, 1977c:17).

In the late 1980s and early 1990s, scientists at the Bevalac sought to identify the mysterious substance known as quark matter by studying the particles produced in heavy-ion collisions.

Quark matter is a form of matter—predicted but never yet observed—that consists of free quarks (the ultimate particle-like constituent of matter) and gluons (the carrier of the force that binds particles together) in a kind of nuclear soup. Quark matter is thought to have been the dominant state of matter at one point shortly after the Big Bang, and may still be present in the cores of neutron stars left over from exploding supernovae. A major current goal of nuclear science is to create and study quark matter in the laboratory by colliding heavy nuclei (ions) at high energies. (Goldhaber quoted in LBL, 1992b:1)

In addition, the LBL Nuclear Science Division's dilepton spectrometer team (DLS) led by Lee Schroeder and Chuck Naudet studied certain very rare particles produced in heavy-ion collisions. These rare particles, which occur only once in a million events, provided "a unique view of the earliest moments of collisions between heavy ions" (Goldhaber quoted in LBL, 1992b:1).

In a typical DLS experiment, the researchers varied factors like the mass of the projectile and target nuclei, the energy of the beam, and the density reached during the collision. These variations were reflected in the mass of the intermediate particle that linked the primary pions created in the collision to the electron/positron pair that was eventually detected. The spectrum of these masses provided information on how the pions propagated in hot, dense, nuclear matter. The first important DLS observation, in 1986, was that the pion annihilation process is the main mechanism for electron pair production in heavy-ion collisions at high mass (Goldhaber quoted in LBL, 1992b:1).

## Bevatron Closure

The Bevatron/Bevalac research complex closed in February, 1993, 39 years to the week after the first subatomic particle beam was circulated. The decision was made by DOE after several years of deliberation, and in spite of last-minute appeals by NASA, which sponsored the facility's cosmic-ray research. An article in the Berkeley Lab periodical *Currents*, described the decision as a primarily political one, in a period of budget shortfalls. "The Bevalac was, in essence, a victim not of scientific obsolescence but of today's adverse economic climate. The money could not be found to fund a Berkeley Lab proposal to keep the accelerator running for ground-based cosmic-ray experiments that would help assess radiation risks to astronauts on deep-space missions" (LBNL, 1992:1).

Judith Goldhaber, science writer for Berkeley Lab publications, summarized the achievements of the Bevatron/Bevalac, emphasizing the extraordinary versatility that allowed the facility to flourish as long as it had.

In the past, LBNL's Bevalac was often snatched from seemingly inevitable closure, to be reborn each time into a whole new productive chapter of its career. But now it seems to have finally used up all of its nine lives. Since its commissioning almost 40 years ago, the venerable particle accelerator has made major contributions to four distinct areas of research: high-energy particle physics, nuclear heavy-ion physics, medical research and therapy, and space-related studies of radiation damage and heavy particles in space.

As the Bevatron/Bevalac neared the end of its usefulness in each of these fields, the area of research it had pioneered moved to other facilities around the nation. Thus, particle physics continues at accelerators such as Fermilab's Tevatron, [and] SLAC's colliders...Heavy-ion nuclear studies will be the major focus at the new Relativistic Heavy Ion Collider (RHIC) at Brookhaven, and experiments in heavy-ion therapy led to design of dedicated medical accelerators such as the Proton Cancer Treatment Center at Loma Linda University Medical Center, and the proposed proton therapy facility at the UC Davis Medical Center. (LBNL, 1992:1)

The original version of the accelerator, the Bevatron, has been called (by physicist Ed Lofgren, who was in charge of its operations from 1954 until his retirement from the position in 1979) "the last of the great accelerators built in...the Lawrence style,'...durable and adaptable. That's why it's not surprising that the Bevatron has endured and adapted so well over the years."



## Overview of the Historic Significance of the Bevatron

Only the highlights of the many years of scientific work at the Bevatron can be described here. Although many discoveries relating to atomic structure and function were made at the Rad Lab, the focus for this discussion will be on Nobel Prize-winning experiments and some of the significant persons associated with the Bevatron.

### Nobel Prize-Winning Research

#### ANTIPROTONS: NOBEL PRIZE TO EMILIO SEGRÈ AND OWEN CHAMBERLAIN, 1959

The existence of the antiproton, the antiparticle of the proton (nucleus of the hydrogen atom) had been theorized since 1930. It is now known, in relativistic quantum theory predictions, that every subatomic particle has an antiparticle, identical in every respect except that all charge-like properties (electric charge, strangeness, and charm) are opposite (Barklow and Perl, 1987:11).

Antiparticles are bits of matter that have properties exactly opposite to their counterparts in ordinary matter. They do not normally exist in the ordinary world of matter, and if produced they exist for only a short time, for when they collide with ordinary particles they are annihilated with them. The result of the annihilation is the creation of other particles that usually decay quickly and dissipate into energy.

At the beginning of 1955, when scientists at the Bevatron began the search for the antiproton (the negative proton) the division of the particle panoply (a complete covering or array of something) into particles and antiparticles had not yet been fully established, and some physicists doubted whether the antiproton existed (Riordan, 1987:66). However, most physicists at Berkeley Lab "were firmly convinced that antiprotons were being created in the nuclear debris formed when protons in the Bevatron beam struck a target of copper (Figs. 30–32). The trick was to catch and detect them" (Goldhaber, 1984:2).

The Bevatron, capable of boosting protons to energies of 6 BeV, was the only accelerator operating in 1955 with enough energy to produce antiprotons. Different teams of scientists at the Bevatron entered into a kind of competitive race to find the antiproton (Fig. 33). Physicist Edward Lofgren played a substantial part in the process, both as leader of one of the teams and as Bevatron director responsible for coordinating and scheduling the use of the machine (Heilbron et al., 1981:83–84).

A team of scientists led by physicists Owen Chamberlain and Emilio Segrè, using three magnetic quadrupole lenses to focus antiprotons onto electronic counters—scintillation counters and Cerenkov counters—found clear evidence of a negatively charged particle with exactly the same mass as a proton—the antiproton (Fig. 34). Two members of their team who made important contributions to the discovery were Clyde Wiegand (Fig. 35), and Thomas Ypsilantis (Riordan, 1987:66–67; Heilbron et al., 1981:81–85).

This first discovery of the antiproton through the measurement of its mass was quickly confirmed by a team led by Eduardo Amaldi in Rome and Gerson Goldhaber at Berkeley Lab, who found the tracks of the collisions of protons and antiprotons in photographic emulsion plates. Photographic emulsions are stacks of photographic film that are exposed by the ionization tracks of energetic charged particles. The image of the tracks can be observed when the film is developed (Goldhaber, 1989:267; Westfall, 1988:409).

Segrè and Chamberlain won the Nobel Prize in 1959 for their experiment. Chamberlain discussed the importance of the discovery in a retrospective essay published in 1989. "In assessing the impact of the discovery on physics, I would say it was certainly no surprise. Most theorists predicted that the antiproton was there to be found when conditions were right. Still, the discovery cleared the air: It allowed people to proceed more confidently into a rewarding future" (Chamberlain, 1989:273-284).

In July-August, 1956, about a year after the discovery of the antiproton at UCRL, a second antiparticle, the antineutron, was discovered by another UCRL experimental group—William Wenzel, Bruce Cork, Glenn Lambertson, and Oreste Piccioni.

#### DISCOVERY OF THE RESONANCES: NOBEL PRIZE TO LUIS ALVAREZ, 1968

"Perhaps the farthest reaching of the discoveries made with the Bevatron were the so-called 'resonances' or energies at which fleeting combinations of particles occur" (Heilbron et al., 1981:94).

Resonances are particles whose lifetimes are on the order of  $10^{-23}$  second—too short to leave visible tracks using the conventional instruments of this period. Such particles travel about a trillionth of an inch before decaying into two or three other particles. Bubble chamber photographs showed only a spray of tracks at the point where the resonance was formed. The first resonance was discovered by Enrico Fermi in Chicago in 1952. Physicists subsequently undertook analysis of these spray patterns.

The first resonances found at Berkeley were a hyperon (any of several elementary particles having a mass between that of a neutron and a deuteron) and two pions, in 1960. The Berkeley group, working with the 15-inch bubble chamber, then found the first kaon resonance and another hyperon resonance.

Luis Alvarez's 72-inch bubble chamber was the most advanced tool for detection of resonances in the early 1960s. The first vector meson,  $K^*$ , was discovered at Berkeley Lab in 1960. By 1961 a pion-pion resonance, and a three-pion resonance led the way to a new era of resonance discoveries in the 1960s (Riordan, 1987:80-81).

Alvarez won the Nobel Prize in physics in 1968 for "the discovery of a large number of resonance states, made possible through your development of the technique of using hydrogen bubble chambers and data analysis." The award was given in recognition of two related contributions: 1) Alvarez's development of the bubble chamber for observing high-energy atomic interactions—the use of large liquid hydrogen bubble chambers and computer-linked data processing systems; 2) Alvarez's involvement in finding 18 of the resonances, which were either discovered or codiscovered in film from one of the two big Rad Lab bubble chambers, the 15-inch or the 72-inch.

At a press conference at the time of the announcement of his Nobel Prize, Alvarez gave full credit to Donald Glaser, the inventor of the bubble chamber, and to the team who worked with him, including Donald Gow, who "played the greatest role in the development of the hydrogen chambers," Frank Solmitz and Art Rosenfeld, who led the computer development for his group, and Paul Hernandez, who was the chief engineer of the 72-inch bubble chamber. Among Alvarez's students in the pioneering bubble chamber work were M. Lynn Stevenson and Frank Crawford (Stevenson, 1993a, 1993b:2). Alvarez recalled the thrill of his pioneering work at the Bevatron.

The early days at the Bevatron were unbelievably exciting; we were repeating and extending the work that had been done by cosmic-ray physicists in the past 20 years. But our 'cosmic rays' traveled horizontally instead of vertically, were billions of times more intense, and ended up in our bubble chambers, where we could take a good look at them! (Quoted in Goldhaber, 1984:2)

#### THEORY OF PARITY NONCONSERVATION: NOBEL PRIZE TO TSUNG-DAO LEE AND CHEN NING ("FRANK") YANG, 1957, INDIRECT CONNECTION TO BEVATRON

Until 1956, almost all physicists believed in the conservation of parity, or the mirror symmetry between left and right. Before the Lee-Yang paper, it had become almost a credo that mirror invariance (parity conservation) is an a priori property of the laws of nature rather than an hypothesis to be tested by experiment" (Telegdi, 1989:465). Parity symmetry had been used to make predictions in atomic and nuclear physics. Even after initial experiments raised questions, "in many laboratories, both in the United States and in Europe, parity violation was considered too wild a hypothesis to warrant an all-out experimental effort" (Telegdi, 1990:469).

Lee (of Columbia University ) and Yang (at Princeton University) found that parity was sacrificed in some weak interactions involving mesons and hyperons. While working as visiting scientists at Brookhaven National Laboratory, they correctly predicted in 1956 that the weak nuclear force, which causes radioactivity and the slow decay of many subatomic particles, violated parity, the symmetry of left and right. This was the "first known example of a lack of symmetry in nature" (Gerson Goldhaber, quoted in Goldhaber, 1984:2). Parity symmetry is therefore only observed in the strong nuclear force, which holds atomic nuclei together, and in strong nuclear interactions (Heilbron et al., 1981:81; Riordan, 1987:195; Bernstein, 1989:35,38; Goldhaber, 1984:1).

Scientists at the Bevatron made experimental observations of the subatomic particles, K mesons, that contributed significantly to the theory of parity nonconservation—that parity does not hold in some cases. Physicist Gerson Goldhaber, who participated in this early work at the Bevatron, has described the contribution of Berkeley scientists.

Two important observations emerged from these early studies of K mesons at the Bevatron. First, what had been believed to be two different kinds of K particles were found to be indistinguishable, even though one kind decays into two pions and the other into three. Dick Dalitz suggested

that the difference lay in their parity—right handedness or left handedness—and T. D. Lee and Frank Yang hit on the explanation: that parity was not being conserved in this decay. (Quoted in Goldhaber, 1984:2; Dalitz, 1989:434–457)

## THEORY OF STRANGENESS AND THE EIGHTFOLD WAY: NOBEL PRIZE TO MURRAY GELL-MANN, A CAL TECH PHYSICIST, 1969, INDIRECT CONNECTION TO BEVATRON

Berkeley emulsion groups contributed to Gell-Mann's identification of so-called strange particles that had novel isotopic spin assignments. "The positively charged  $K^+$  and the negatively charged  $K^-$  turned out to have very different interaction properties, and this confirmed Murray Gell-Mann's suggestion of a new property of matter, strangeness" (Gerson Goldhaber quoted in Goldhaber, 1984:2). Gell-Mann introduced a new quantum number, the strangeness  $S$ . "What took this scheme beyond mere taxonomy was Gell-Mann's imposition of an approximate conservation law, namely, that in all strong processes, the kind in which the strange particles are produced, strangeness is conserved" (Quote in Bernstein, 1989:54; Heilbron et al., 1981:81; Gell-Mann, 1989:694–711).

Lawrence Radiation Laboratory physicists Sheldon Glashow and George Kalbfleisch discovered a new elementary particle, the  $Y^*1$  that provided important confirmation of Gell-Mann's theory of the Eightfold Way. This theory suggests that,

The basic components of strongly interacting matter, the so-called 'elementary' particles, fall naturally into groups, or multiplets, of particles, with the majority of the particles arrayed in groups of eight called octets. In the 'ground' state, there are four such octets, one collection often called a decuplet, and several singlets. Other particles that have been discovered are seen as recurrences of these particles at higher energy states. The importance of the theory, aside from the question of its theoretical validity, lies in the fact that it permits the prediction of yet undiscovered particles. In this sense, the 'eightfold way' scheme might serve modern physics for subatomic particles as the periodic chart of the chemical elements has served chemists in the past. Such a scheme would permit physicists to predict the properties of nuclear states of matter from a limited knowledge of the more familiar particles. (LRL, 1963a:1)

## Scientists Associated with the Bevatron

The following discussion classifies significant persons in two groups. In the first group are the Nobel Prize-winning physicists whose work is associated with the Bevatron; the second group is composed of the many scientists, engineers, and physicians who conducted important scientific work at the Bevatron and Bevalac, or who contributed significantly to the design and operation of the accelerator.

Ernest Orlando Lawrence (1901–1958) and Edwin McMillan (1907–1991):

Although their Nobel Prizes were not directly associated with the Bevatron or Bevalac, they played leading roles as Laboratory directors in the creation of the facilities. Lawrence's invention of the cyclotron in 1929, and McMillan's idea of phase stability in 1945, were major scientific contributions that provided a foundation for development of the Bevatron.

All of the people on the following list are physicists unless otherwise noted. All of them were (and many still are) on the Berkeley Lab staff.

Nobel Prize winners directly associated with the Bevatron:

Emilio Segrè (1905–1989) and Owen Chamberlain (1920–):

Jointly awarded the Nobel Prize in 1959 for their discovery of the antiproton in an experiment at the Bevatron. This experiment is described briefly in the Overview of the Historic Significance section in this record.

Luis Alvarez (1911–1988):

Won the Nobel Prize in 1968 for his development of the bubble chamber particle detector (originally invented by Donald Glaser) and for his role in finding 18 particle resonances with Rad Lab bubble chambers used in conjunction with the Bevatron.

Many other researchers have been associated with the Bevatron/Bevalac. The following are representative of the scientists and engineers associated with the Bevatron and Bevalac:

José Alonso: Bevalac Director; nuclear physicist in Bevalac Biomedical Facility

Robert Birge: Experimental work with propane bubble chambers

Eleanor Blakely: Researcher affiliated with the Biomedical Facility

William Brobeck: Engineer, Chief Designer of the Bevatron

Joseph Castro: In charge of clinical medical program at Bevalac

Bruce Cork: Member of team that discovered antineutron in 1956; worked on instrumentation and experiments from early period (Fig. 36)

Ben Feinberg: Head of operations at the end of the Bevalac

Albert Ghiorso: Nuclear chemist at HILAC who conceived idea for Bevalac

Gerson Goldhaber: Experimental work with nuclear emulsions

Donald Gow: Assisted Luis Alvarez in development of bubble chamber

Hermann Gruner: Built the Bevalac and was head of Accelerator Division at the Rad Lab after Edward Lofgren's retirement

Walter Hartsough: In charge of operations at Bevatron/Bevalac for many years

Paul Hernandez: Assisted Alvarez with the hydrogen bubble chamber detector

Harry Heckman: Conducted first Bevalac experiments on projectile fragmentation

Glenn Lambertson: Member of team that discovered antineutron in 1956; worked on instrumentation and experiments from early period

Edward J. Lofgren: First director of Bevatron, leader of Bevalac development, Director of Accelerator Division at Rad Lab

Shoji Nagamiya: Leader of the Japanese research group at the Bevalac

Charles Naudet: Worked with Lee Schroeder on heavy-ion research

Oreste Piccioni: Member of team that discovered antineutron in 1956

Art Poskanzer, Hans-Georg Ritter, and Hans Gutbrod: Members of the team that discovered the directed flow of nuclear matter

Wilson Powell: Experimental work with propane bubble chambers

Howel Pugh: Scientific Director of the Bevalac for many years

Lynn Stevenson: Member of Luis Alvarez's team in bubble chamber experiments

Reinhard Stock: Leader of the German research group at the Bevalac

James Symons and Hank Crawford: Conducted research using HISS (Heavy Ion Spin Spectrometer)

Isao Tanihata: Discovered neutron halo in lithium

Cornelius Tobias: Conducted cancer therapy research at Bevalac

George Trilling: Experimental work with nuclear emulsions

William Wenzel: Member of team that discovered antineutron in 1956; work on instrumentation and experiments from early period

Clyde Wiegand: Member of the Segrè/Chamberlain team that discovered antiproton

Gordon Wozniak and Luciano Moretto: Investigated complex fragment emission of heavy ions

## Architecture of the Bevatron Building

The terms Bevatron and Bevalac commonly refer to a complex of buildings and the machines inside them. The buildings and machines functioned together for common purposes, and in several ways the distinction between buildings and machines is blurred. At the same time, a natural distinction exists between buildings and machines. From the beginning, they were the concerns of two separate sets of designers and builders. Buildings were constructed under the building codes and other applicable laws of the State of California; building records have always been kept separate from machine and instrument records. The purpose of this section is to discuss the chronology of building construction and to summarize the architectural features of the Bevatron.

### Construction History of the Bevatron Building Complex

The buildings of the Bevatron/Bevalac, and associated buildings, which still exist are the Bevatron (Building 51, 51A, and 51B), the HILAC (Building 71), and the Accelerator Design Building (Building 64). Building 51 and Building 71 together comprised the main components of the Bevalac accelerator. (These buildings are described to provide the context of the construction history; however, we would like to note that only Buildings 51 and 51A are of historical significance.) Building 64 served first as a support building for the Bevatron and later for the Bevalac. Building 59—no longer in existence—housed the bubble chamber and was one of several particle detection facilities built in the flat, open area adjacent to, and northwest of, the Bevatron. The area occupied by the Bubble Chamber Building was subsequently covered by the External Proton Beam Hall (EPB) (B51B) in 1967. Building 59 was, at the time of its construction, the most prominent detection facility outside of the shelter of the Bevatron. After it was demolished, most subsequent detection facilities were inside the Bevatron complex (including the EPB), and lay largely on the machine-side of the machine/building divide. Other experiment buildings have been relatively small and unobtrusive.

The buildings of the Bevatron were frequently modified and expanded throughout their years of service from the early 1950s to February 1993. Since the Bevatron/Bevalac was closed in February 1993, some of the machines and other furnishings which the buildings housed have been removed. The history of the Bevatron and other associated buildings are introduced as a whole, and then treated separately below.

### BUILDING SITE CHARACTERISTICS

The Bevatron is located on a hill east of the campus of the University of California (Fig. 37) at Berkeley that was a large, sparsely developed area first assigned to the UC Radiation Laboratory in 1940. The Bevatron was built on an undeveloped piece of land called the Wilson Tract which had been allocated for the UC Radiation Laboratory. A contract for grading and drainage of the site was let in August, 1948. At the time the Bevatron was built, the principal building of the Laboratory was the 184-inch Cyclotron

(Gebhard, 1987). A comparison of the 184-inch Cyclotron and the Bevatron will illustrate the nature of the Bevatron Building.

The Cyclotron was sited prominently so that it could be seen from the main campus and a wide area below. It occupied a key spot on axis with the plan of the main campus, and its dome was designed to be compatible with the Beaux-Arts classical buildings on the campus. In its design and siting, the Cyclotron was symbolically powerful, expressing its relationship to the campus and established fields of learning to a wide public.

By comparison, the Bevatron was situated below the Cyclotron on the hill so that it was barely visible from below (until the EPB hall was built in 1965–1969). Its siting and design had no relation to the main campus plan. In appearance, it was a modern industrial building that could have been sited anywhere.

#### BEVATRON BUILDING (BUILDING 51)

##### *Phase 1. Building 51, The Bevatron Building*

The Bevatron Building was designed by the San Francisco architectural firm of Masten and Hurd. The earliest dated scheme was a drawing of September 9, 1947. A signed perspective dated December 10, 1948, indicates that there was a general approach to the building in place by that time (Figs. 38, 39). A complete set of as-built drawings on file at the Berkeley Lab Facilities Department is dated June 6, 1949. The index to subcontracts of the Facilities Department of Berkeley Lab shows a contract let for construction in June 1949 (Fig. 40). Construction photographs dramatize the difficulty of building on a hill (Figs. 41–43) which was reached by a narrow, winding road, in a series of views of a truck hauling one of the 93-foot long cranes to the site. Photographs show the building as complete before the machines were finished (e.g., Berkeley Lab Photo: Box 1, Book 1, No. 306), and illustrate the role of the building in the completion of the machines, with the winding of the magnet coil using the big crane.

As built, the Bevatron consisted of a principal circular magnet room with a quarter-circle, two-story, shop-and-office wing along the south side of the circle, and a large rectangular mechanical wing tangent to the circle on the northeast (Fig. 44). The circular magnet room is 220 feet in diameter and 40 feet high between the main floor and the bottom of two tiers of roof trusses. A pair of 30-ton cranes, mounted on crane rails at the center, and the circumference of the space were used to install and repair the magnet below and to handle later additions such as concrete shield blocks. The 34-foot-wide shop-and-office wing included spaces designated for control room, electronic equipment and shops, and office space for researchers and engineers (Figs. 45–48). The mechanical wing (310 x 71.5 feet) housed the fan room for cooling the magnet, the motor/generator room for providing power to the magnet, and miscellaneous shops. Its exterior is clad in corrugated transite panels and bands of steel sash and louvered ventilators.

Under a separate design and contract, a cooling tower was built outside the circle in the area between the shop-and-office wing and the mechanical wing. This was in place by May 1951. It was demolished in 1993 as a collapse hazard.



Another contract in October 1953 was for construction of a ring of foundations to support heavy concrete shielding around the magnet. This was a ring 10 to 13 feet wide of concrete caissons with an inner radius of 60 to 65 feet. The designer was Robert A. McGuire of Huber and Knapik, engineers.

Little is known about the design process or program apart from what can be inferred from the drawings and the building itself. William Brobeck, designer of the Bevatron machine, was not involved in the design of the building. The architects, Masten and Hurd, were respected designers of public schools and other school buildings and had worked for the University of California on other projects (Figs. 49, 50).

Although the design of the building is unique among industrial buildings in general and accelerators in particular, it is characteristic of industrial buildings of the period, in that its form was generated from its very specific functional needs. It was designed from the inside out—without preconceptions about its shape. It provided shelter for its machines, space for circulation of personnel, and room for future expansion—all in a setting of natural light and adequate ventilation (Figs. 51–59).

#### *Phase 2. Building 51 Addition, Building 51A.*

The Building 51 Addition was an expansion of the principal circular magnet room of the Bevatron on its northwest periphery (Fig. 60). It ran one-third of the way around the circle to the south from the mechanical wing. It was 65 feet wide except at the junction with the mechanical wing where it included a new generator room, and was about 80 feet wide. It was designed together with Building 59 to the northwest, to which it was linked by a heavy concrete pad. Both buildings were designed by the San Francisco firm of Milton T. Pflueger, Architect, in plans dated February 11, 1957. Huber and Knapik were structural engineers, and Buonaccorsi and Murray were mechanical and electrical engineers. A contract was let for construction in February 1957.

The Building 51 Addition was a steel-frame structure clad in corrugated transite panels with bands of steel sash windows, to match the original Bevatron Building. Except for the new generator room, it was about 40 feet high from the floor to the bottom chord of the roof truss. The roof was supported by a Pratt truss so that there was a single, slightly curving, open space below. This space was served by a 30-ton crane that was curved to fit the exterior curvature of Building 51.

Also in this period, new cooling towers were built in the area just outside the circle between the shop-and-office wing and the mechanical wing. These were built under contracts let in May 1956 and April 1959.

The designation Building 51A has come to include both this 1957 addition and a smaller addition in 1961, described below.

#### *Phase 3. Major Bevatron Improvements*

A group of substantial modifications to the Bevatron were undertaken in 1961 to 1963, commonly referred to as Major Bevatron Improvements. The architectural modifications required to accommodate these changes were primarily inside—many of them underground. The major areas of change in the building were initially to provide additional shielding for the magnet, to accommodate a new injector and an external

beam, to remodel the north experimental area, and to build the west experimental area addition, and a five-story south addition. All but the south addition were realized.

To accommodate complete shielding of the magnet, new walls had to be built inside and outside the magnet ring which would be spanned with a roof, so that the magnet was completely enclosed by massive blocks of concrete. Foundations for the outer shielding walls had been built in 1953 and strengthened in 1960. New foundations had to be built for the inner shielding walls. Tunnels and ducts were built underneath the shielding which required additional strengthening and reconstruction of the inner wall area to maintain the inner crane rail above. This area was referred to as the new Center Structure, and more commonly as the Igloo. The shielding foundation and support structures were designed by Huber and Knapik. Moran, Proctor, Mueser and Rutledge of New York, Consulting Engineers, and Keller and Gannon, Mechanical Engineers of San Francisco were associated on the project. The center structure was designed by Earl and Wright of San Francisco. This work was performed under a contract let in July 1961.

To accommodate a new injector, the original electricians and maintenance machinist's shops in the mechanical wing of the building were combined into a single space, and new foundations were provided.

For the construction of an external beam line beyond the northwest edge of the building a foundation for shielding was built. This work was all designed by the same team that designed the shielding and was built between May 1961 and October 1962.

The north experimental area, in the Building 51 Addition just west of the mechanical wing, received new foundations, new partitions including a soundproof wall for insulation from the motor/generator room, and a heavy duty floor. This work was performed under a contract let in May 1961.

The West Experimental Area Addition (Building 51A) was designed by Earl and Wright and was built under contracts let in July 1961 and June 1962. This expanded the Building 51 Addition of 1957, described in Phase II above, around the circle two bays ( $1/12$  of the circle) until it met the original shop-and-office wing. Together with the Building 51 Addition, this was designated as Building 51A.

#### *Phase 4. External Proton Beam (EPB) Hall, Building 51B*

The External Proton Beam Hall was designed by Earl and Wright, Consulting Engineers of San Francisco, in several stages. The first stage was the External Beam Craneway, whose design is shown in a set of as-built drawings dated December 14, 1965. A contract for this work was let in December 1965. The design for the External Beam Craneway Roof is shown in a set of drawings dated August 19, 1966. The External Beam Craneway was built around and over Building 59 which was demolished according to drawings dated January 30, 1967. The design for the EPB hall siding is shown in a set of drawings dated July 1969. A contract for this work was let in July 1969.

The EBP Hall projects northwest from the edge of that portion of the Bevatron designated as Building 51A. It is a rectangular steel-frame structure measuring about 290 by 144 feet and 74 feet high. It is 52 feet high from the floor to the bottom chord of

the system of roof trusses. The roof is supported by a grid of Pratt trusses. The EPB hall is open for 21 feet around its base, and enclosed by large metal and plastic wall panels above. These panels measure 53 by 30 feet and are blue-green in color. The interior is a large craneway with a clearance of 39.5 feet.

It was only with the application of siding to the EPB Hall that any portion of the Bevatron became conspicuous from the City of Berkeley. The main floor level for both buildings is at an elevation of 710 feet above sea level. The Bevatron is about 68 feet to the top of its conical roof; the EPB Hall is 74 feet high over a much larger area and is much bulkier. The Bevatron is built back into the hill so that portions of it are below grade. The EPB Hall is in front of the Bevatron, blocking any glimpse of the Bevatron that might otherwise exist. The EPB hall is one of five LBL buildings on the hill that can be widely seen from below, also including the Cyclotron, Building 50, Building 88, and Building 90.

#### *Phase 5. Earthquake Rehabilitation Plan*

Work began under a contract let in January 1980, on a plan to strengthen the Bevatron against earthquakes. This plan was developed by John J. Earle, structural engineer with the LBL Plant Engineering Department (predecessor of the Berkeley Lab Facilities Department).

Some of the principal Bevatron project construction contracts were let to the following companies:

Installation of Magnet Assembly: Gilmore Steel

Wiring Raceway: Garlervy; California Steel Company

Electrical Power Installation: Severin & Brayer Electrical

Flywheel and Motor/Generators: G. W. Thomas Drayage and Rigging

Concrete Radiation Shield Foundation: O. C. Jones

#### **BUBBLE CHAMBER BUILDING (BUILDING 59, DEMOLISHED 1967)**

Building 59 was a freestanding structure built northwest of the Bevatron but connected to it by a heavy concrete pad. It was designed and built at the same time as the Building 51 Addition, shown in as-built plans dated February 11, 1957 prepared by Milton T. Pflueger, Architect. A contract was let for construction of these buildings in February 1957.

The Bubble Chamber Building was in two principal parts. It was a pair of parallel rectangles of unequal size and height, a low office and shop wing (112 x 29 feet) on the north, and a 40 foot high crane bay (101 x 40 feet) in the south. The low wing included rooms for mechanical equipment, a shop, and a control room, and the high wing housed the bubble chamber. Both wings had solid concrete-panel lower walls and bands of corrugated translucent plastic above.

Construction photographs show steelwork for the EPB hall built around Building 59 and the demolition of Building 59 only when the EPB hall was nearly finished, in 1967.

## ANCILLARY BUILDINGS

### *Accelerator Design Building (Building 64)*

The Accelerator Design Building was designed and built in stages. The first stage is shown in a set of as-built drawings prepared by Indenco Engineers of Oakland, dated January 3, 1951, and was built under a contract let in January 1951. The original building consisted of two, two-story rectangular volumes in series, with a higher and wider section close to the north end of Building 51, and a lower and narrower section to the north of the first section. The larger section enclosed a single, partitionable space broken by two interior rows of columns on the ground floor, and a column-free loft upstairs under a trussed roof. The smaller volume housed offices.

The second phase, at the west end of the original building, and at an angle to it, is shown in as-built drawings prepared by Corlett and Spackman, dated June 27, 1955, and was built under a contract let in June 1955. This addition housed offices and a loft area for mechanical engineering on the ground floor, and offices and a loft area for plant engineering upstairs.

In 1960, the Accelerator Design Building underwent major modifications, including installation of a 30-ton crane and a cooling tower on the hill behind the building. The interior was reorganized so that, on the ground floor, bubble chambers occupied the north end of the building, electronics engineers and installers occupied the middle, and testing equipment occupied the south end in a two-story space created by the removal of the second floor. Upstairs, mechanical engineering occupied the middle between offices to the north end and the upper part of the crane bay to the south. In 1971, the original central entrance to the building was converted to an experimental area.

In 1972, new foundations were designed for the 50-MeV HILAC. After formation of the Bevalac in 1974, Building 64 housed the Bevalac Engineering Group. Later it housed the Accelerator and Medical Physics Groups.

### *HILAC Building (Building 71)*

The existing building was linked to the Bevatron by way of the Beam Transfer Line when the Bevalac was established. A detailed description of the HILAC Building is not part of this HAER documentation.

## BUILDINGS ASSOCIATED WITH BEVALAC OPERATION

The establishment of the Bevalac involved modifying and linking the machinery in two existing buildings, the Bevatron and the HILAC, but has not involved major modifications of the buildings themselves, except to accommodate additional experimental equipment. Those which were considered buildings and are recorded in the building records are described below.

### *HISS Users Buildings*

Two prefabricated buildings, so-called Butler Buildings, described on drawings dated February 23, 1979 as Relocatable Experimental Shelters, were designed by C.B.S. Construction, Inc., of Oakland, to be built at the north end of the EPB hall. Both were small, windowless rectangular structures with light steel frames, and vertical metal

exterior cladding. Building No. 1, with three rooms, was 24 x 60 feet; Building No. 2, with a single interior space, was 30 x 50 feet.

#### *Experimental Computer Enclosure (Building 51L)*

The Experimental Computer Enclosure is a one-story rectangular structure south of the EPB hall near its junction with the Bevatron. The building measures 24 x 36 feet. It contains a wide central room flanked by narrow rooms, each with a small separate room at the rear. It is a light steel-frame structure with vertical siding and a very slightly pitched roof. It was built according to a set of architectural drawings dated July 19, 1983.

#### *Bevalac Patient Facility (Building 51N)*

The Bevalac Patient Facility is a small building located inside the Bevatron Experimental Area, on the north side of the magnet room. This is a light steel-frame structure with "prefinished" metal siding and foil-faced fiberglass batt insulation. It is rectangular in plan (32 x 20 feet). Stud wall partitions divide the interior along a central corridor, with a tech-station, viewing room, and toilets on one side, and a waiting room, dark room, and exam room on the other. It was designed according to a site plan and other drawings from April, 1987.

### **Architecture of the Bevatron Building Complex**

#### **ACCELERATOR BUILDING**

The first modern subatomic particle accelerators were built in existing lab space at the University of California at Berkeley in the late 1920s and early 1930s. The first cyclotron, with a diameter of five inches, was used by E.O. Lawrence in a lab in Le Conte Hall on the main campus of the University of California at Berkeley in 1929. Beginning in 1931, a series of increasingly larger cyclotrons were built in a room in a building originally designated the Civil Engineering Test Laboratory (later renamed the Old Radiation Laboratory) on Hearst Street adjacent to the main campus. Lawrence described this as "a large frame structure with several substantial concrete piers in the rooms" (Lawrence cited in Heilbron, 1989:113). A photograph of one of the cyclotrons in this building showed walls of ordinary wood construction in the background. A photograph published in 1960 of a 1.3 BeV electron synchrotron at Cornell University shows that as late as the 1950s, unmodified lab space was used for particle accelerators (Wilson and Littauer, 1960:Plate XI).

As accelerators grew larger and their needs for power increased, new accelerators began to be built. The first of these was the Cyclotron Building for the University of California Radiation Lab (currently designated Building 6) on the hill east of the main campus. Construction of this building (Building 6) began in 1940; the Cyclotron went into operation in 1942. The Cyclotron Building was designed by Arthur Brown Jr., official campus architect, and one of the most distinguished architects of his day in California. He also designed, alone or with partners, the city halls in San Francisco, Berkeley, and Pasadena; the Opera House and Coit Tower in San Francisco; and Hoover Tower at Stanford University. The Cyclotron Building was carefully sited and designed to express the pre-eminence of science in the modern university and the modern world. Its siting

was on axis with the main campus plan below, and its carefully proportioned dome was in harmony with the Beaux-Arts buildings of the campus.

Except for its siting and dome, the design of the Cyclotron Building was the product of standard modern practice for the design of industrial buildings. A later article on the design of accelerator buildings expressed the process concisely as follows:

"Architectural form usually emerges from a site, a list of project requirements and a budget provided by the client to his architect" (Leposky, 1969:22). In other words, the building is largely the result of practical needs and constraints. Like other industrial structures, its form is the product of the activities and the machines inside.

After World War II, planning began—with the involvement of the AEC—for new accelerator facilities at Brookhaven (New York), and Berkeley. These would be proton synchrotrons called the Cosmotron at Brookhaven and the Bevatron at Berkeley. They were approved at the same time, although the Cosmotron went into operation in 1952, two years before the Bevatron. The approach taken to the design of buildings for two machines of the same type at the same time in the same country begins to illustrate the variety of appearances that were possible, and that characterize the increasing number of accelerator buildings around the world in the years that followed. One might say that for one type of building—the accelerator building—various styles were possible. Accelerator buildings could be symmetrical or not, they could appear grand or factory-like, they could be ornamented in a modern way or with historical references. Designers of the Bevatron followed up to a point the example of the Cyclotron, which had a 24-sided, circular main building clad in transite panels and horizontal bands of windows; at the same time, the Bevatron was less symmetrical and it lacked historical ornamental references. Although the Cyclotron and Bevatron buildings reflected the shape of their respective accelerator machines, the Cosmotron Building did not. Similar machines and activities were sheltered by a symmetrical, generally rectangular building whose appearance reflected linear craneways inside, rather than the shape of the accelerator apparatus.

Beginning in the 1950s, many new accelerators would be built in the United States, the Soviet Union, Western Europe, and Japan. Designers of buildings for these machines were faced with a consistent set of problems, to provide shelter and services for accelerator machines and power sources, experiments, control systems, and radiation shielding, and to provide circulation space, room to expand, cranes, and light. To this common set of problems, the designers brought a consistent approach to design, common in designing for industry, in which the form was generated by the specific needs of the situation. The great variety in specific circumstances, including the type of accelerator (linear, proton synchrotron), the size of the machine and power needs, the site, the presence or lack of existing lab and office facilities, produced a great variety of buildings.

Discussed in traditional terms of structure, plan and function, and image, a few generalizations can be made about accelerator buildings. Structurally, all accelerator buildings appear to be steel-frame or reinforced concrete with heavy concrete foundations. Some accelerators are built partly underground for shielding purposes. Accelerator buildings are varied in plan, with respect to the accommodation of variable

research programs. Plan types include those represented by the mile-long linear accelerator at Stanford (Stanford Linear Accelerator Center), the makeshift accretion of parts of the Bevalac, and the highly ordered, master-planned research campuses of Fermilab near Chicago, and CERN (Organisation Europeenne pour la Recherche Nucleaire) near Geneva. As for architectural image, most are straightforward buildings using modern industrial materials which represent in modest ways the pre-eminence of science and reason. Only a few, like the Cyclotron at Berkeley and the Soviet accelerator at Dubna with its exterior characteristic of Soviet civic architecture—are reminiscent of the overscaled Italian fascist architecture of Mussolini (Jungk, 1968:Plate), possessing larger symbolic or architectural pretensions.

In all of these ways, accelerator buildings are an international building type, the product of twentieth-century attitudes toward planning and design held in all advanced industrial countries. Individualistic touches, such as the dome of the Cyclotron and the exterior cladding of the proton synchrotron at Dubna, are rare and superficial (at Dubna, the magnet room interior is similar to, but larger than, the magnet room of the Bevatron). As an international type, each of several countries produced no more than a few in the early years, and each accelerator and accelerator building was an effort of the national government or a cooperative venture of more than one government, together with leading scientists and universities in those countries.

Finally, like other industrial building types, accelerator buildings are designed to accommodate machines. Some industrial buildings simply shelter machines from the elements so that machines of different types for different processes might simply be moved in or out as needed, like furniture. Other industrial buildings are designed for specific machines and processes. Steel mills, glass factories, flour mills, slaughterhouses, and many gravity-process factories are examples of this type. In these cases, the buildings are designed specifically for a machine process and are essential to the process. In effect, buildings like these are parts of the machinery, reflecting a statement of pre-eminence for the scientific or industrial apparatus and thereby de-emphasizing architectural elements representing individual or social metaphors. In a sense, the absence of architectural metaphor is in itself a statement.

Accelerator buildings are like these industrial buildings. Each one is designed for very specific circumstances (Leposky, 1969:22). Each one is shaped by a variety of forces including the machines to be housed, the site, attitudes to design, and the individuals involved; each one is, in effect, part of the machine. The Bevatron Building (Building 51), for example, has become more complicated and more machine-like as it has been modified over the years. The Bevatron machinery could not operate without it. The Bevatron Building is integrated with the operation of the Bevatron machinery in the following ways: the two cranes in the circular magnet room, and the other cranes in the main experimental area as well as the External Proton Beam Hall (Building 51B), have been essential to the construction, maintenance, and repair of the magnet and other machines; the foundations provide support for very heavy and highly-specialized equipment such as the magnet, the injector, the HISS, and the shielding; the power room is an essential component for running the Bevatron; and the ducts under the floors carry air from the fan room to cool the machine. In this way, the Bevatron Building is like other accelerator buildings, inseparable from the accelerator for which it was built.

## **Architecture of the Bevatron/Bevalac Building Complex**

The Bevatron/Bevalac at Berkeley Lab is a complex of buildings and machines located on a steep site on a hill east of the University of California at Berkeley main campus. Because of the steep topography, it is set among other buildings of the Laboratory that are situated on a limited number of buildable sites; at the same time, the buildings are grouped as much as possible by function. For most of its history, building at the Lab proceeded without the guidance of a master plan. Buildings 51/51A form the Bevatron Building core complex. Building 71 (SuperHILAC Building), Buildings 51B (External Proton Beam Hall) and 64 (Accelerator Design Building), and the Beam Transfer Line, are given brief descriptions below in the interest of establishing the architectural and physical context of the Bevatron Building (Building 51/51A).

The Bevatron/Bevalac consists of two major building groups which were originally built for unrelated purposes and which were built on sites separated by 124 feet in elevation. These are linked by a transfer line, which contains an evacuated aluminum pipe within which accelerated particles traveled from the SuperHILAC (Building 71) above, to Building 64 and the Bevatron (Building 51 and 51A for the purposes of this report) below. Building 71 and Buildings 51 and 64 were built without any design relationship to each other. Building 71 is oriented east-west; Building 51 is oriented in a scattered way northwest-southeast; Building 64, oriented north-south, is in a narrow space between the hill and the EPB Hall (Building 51B) at the Bevatron. Buildings 51 and 71 have multiple additions which obscure the clarity of their images, orientations, and relationships to other buildings. As a result of the difference in elevation and orientation of the buildings, the route of the transfer line is indirect. The pipe of the transfer line is carried partly below ground and partly above ground on wooden frames.

In short, the complex developed over a period of time from independent actions rather than in a single rational planning effort such as occurred at some other accelerators (e.g., CERN in Switzerland). The overall appearance of the Bevalac buildings is disorderly. It has the character of a makeshift lab experiment blown up to the proportion of buildings. Because of the topography, it is difficult to grasp the complex as a whole from the site or from a distance. From a distance, portions of the Bevalac are visible (the EPB hall of the Bevatron is widely visible because of its height, Building 71 can be glimpsed from some vantage points), but nowhere is it possible to see it whole. For anyone unfamiliar with the Bevalac, even when the different parts are seen, there is no obvious reason to understand these parts as a whole.

The elements of the Bevatron/Bevalac are described below in functional order: the Bevatron Building (Building 51/51A), and then the ancillary buildings (Buildings 71, 51B, 64, and the Beam Transfer Line). The descriptions which follow are intended to present a picture of the buildings as they are today, in contrast to the earlier section where the history of construction was presented (Fig. 61).

### **Bevatron Building (Building 51/51A)**

The Bevatron Building (Buildings 51 and 51A) today is a complex, irregularly shaped structure with five principal parts, the design being a consequence of several successive



building campaigns: the circular magnet room, the curving shop-and-office wing on the periphery of the magnet room (Figs. 62–65), the curving experimental area also on the periphery of the magnet room (51A), the rectangular mechanical wing, and the larger rectangular EPB hall (Figs. 66, 67). Inside and around the Bevatron Building are small structures associated with experiments.

The magnet room is at the center of a larger circular area including the shop-and-office wing and the experimental area. Stretching away from this circle are the rectangular mechanical wing in a north-by-northwest direction, and the EPB hall in a northwest direction. The transfer line from the HILAC Building enters the Bevatron between these two wings.

The Bevatron is entirely a steel-frame structure above a much-rebuilt foundation of reinforced concrete (Figs. 68–70). The foundation has been strengthened in places to support the magnet, the injector, the motor/generators and other electrical equipment, and various experimental machinery including the HISS. In addition, the foundation incorporates tunnels for access to the magnet, the accelerator tanks, and the various ducts—for cooling air coming from the fan room and the outside cooling towers to the magnet, for the vacuum pumping system, and for a variety of control-line conduits.

Above this complex foundation, the steel frame is generally exposed inside. Outside, the building is clad in corrugated transite, with clerestory bands of metal sash windows and louvered ventilators.

Visually and functionally, the magnet room is the heart of the Bevatron building. This is a near-circular space (actually a 24-sided polyhedron) spanned by two tiers of trusses with a central column (Fig. 71). The lower tier of trusses is called the roof truss. The upper tier, called the monitor truss, lifts the center of the roof in order to provide space for a ring of ventilators. From the outside, this roof is a shallow cone in two sections. Two 30-ton cranes span the distance from a crane rail around the central column to the periphery of the magnet room. Beneath the cranes is the shielding structure of massive concrete blocks which completely encloses the magnet.

Tangent to the magnet room and extending north by northwest is the mechanical wing. At the north end of this wing is the high, open motor generator room (Fig. 72) where the power is produced to run the Bevatron. At the south end is the fan room for cooling the magnet. In between, the space of the magnet room is extended into this wing in order to house the injector.

The space of the magnet room extends into a space designated on the plans as the experimental area for 10 bays (Building 51A) around the northwest periphery of the magnet room. This space is served by a 30-ton crane which runs along a curving path for its full length.

Projecting beyond the experimental area is another experimental area, the large, high, open space of the EPB hall (Building 51B) with its large craneway. The EPB hall is open at its base and clad in large vertical metal and plastic panels above.

On the south side of the magnet room is the curving two-story shop-and-office wing, including the control room (Fig. 73).

## Future Plans

Currently there are plans to use some of the office and laboratory space in Building 51 to meet space and facility needs to achieve Berkeley Lab's science and technology mission. The potential exists for use of this space for accelerators or other large experimental apparatus. For example, the laboratory is evaluating locations for experimental equipment for its heavy-ion fusion program. However, Berkeley Lab reserves the right to demolish the building in order to meet program and facilities needs, if necessary.

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ADDENDUM TO:  
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PHOTOGRAPHS

WRITTEN HISTORICAL AND DESCRIPTIVE DATA

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